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Final
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Superfluid Helium Tanker (SFHT) Study

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Superfluid Helium Tanker (SFHT) Study

Approved:

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FOREWORD

The Final Program Progress Report documents work conducted by Martin Marietta Astronautics Group, Space Systems, Denver, Colorado, under contract NAS9-17854, Superfluid Helium Tanker (SFHT) study. The contract is administered by the National Aeronautics and Space Administration - Johnson Space Center, Houston, Texas. The NASA Project Manager is Mr. William C. Boyd, Propulsion and Power Division. This report summarizes the results of Task 3 - Conceptual SFHT System Design, Task 4 - Commonality Assessment and Technology Development Recommendations, and Task 5 - Program Plan for SFHT Development. This document conforms to the requirements of DRL-4 (DRD MA-125T).

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Acronym	Definition
AFD	Aft Flight Deck
APS	Active Phase Separator
ARC	Ames Research Center
ASE	Airborne Support Equipment
ASTROMAG	Particle Astrophysics Magnet Facility
AXAF	Advanced X-Ray Astrophysics Facility
BASD	Ball Aerospace Division (Boulder, Colorado)
C&DH	Command and Data Handling
CITE	Cargo Integration Test Equipment
cfm	cubic foot per minute
cg	Center of Gravity
CPPF	Critical Point Phenomena Facility
CSF	Customer Servicing Facility
CRT	Cathode Ray Tube
ELV	Expendable Launch Vehicle
EMU	Extravehicular Mobility Unit
EOS	Earth Observing Satellite
EVA	Extravehicular Activity
FEP	Fountain Effect Pump
FF	Free Flyer
FIRST	Far Infrared/Submillimeter Space Telescope
FP	Fountain Pump
FTS	Flight Telerobotic Servicer
GPC	General Purpose Computer
GRT	Germanium Resistance Thermometer
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
g_o	Acceleration due to gravity at Earth's surface
He	Helium
He-I	Normal Helium
He-II	Superfluid Helium
HLVS	Heater, Level and Valve System
ID	Inner Diameter
IOC	Initial Operational Capability
IOSS	Integrated Orbital Servicing System
IR	Infrared
IRAS	Infrared Astronomical Satellite
IRS	Infrared Spectrometer
IRT	Infrared Telescope
ISO	Infrared Space Observatory
IVA	Intervehicular Activity
IWFMS	Integrated Waste Fluid Management system
JSC	Johnson Space Center
J-T	Joule-Thomson
KSC	Kennedy Space Center
K	Degrees Kelvin
LDR	Large Deployable Reflector
LeRC	Lewis Research Center
LHe	Liquid Helium

Acronym	Definition
LHSF	Liquid Helium Servicing Facility
MEOP	Maximum Expected Operating Pressure
MLI	Multilayer Insulation
MMPS	Microgravity and Materials Processing Sciences Facility
MRMS	Mobile Remote Manipulator System
MSC	Mobile Service Center
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NBP	Normal Boiling Point
NBS	National Bureau of Standards
NHe	Normal Helium
NPSP	Net Positive Suction Pressure
OMV	Orbital Maneuvering Vehicle
OD	Outer Diameter
OPF	Orbiter Processing Facility
ORU	Orbital Replacement Unit
OSCRS	Orbital Spacecraft Consumables Resupply System
P	Pressure
PCR	Payload Changeout Room
PDI	Payload Data Interleaver
PDU	Power Distribution Unit
PGHM	Payload Ground Handling Mechanism
PHSF	Payload Hazardous Servicing Facility
P/L	Payload
POCC	Payload Operations Control Center
PP	Porous Plug
PRT	Platinum Resistance Thermometer
RCM	Remote Connection Mechanism
RCS	Reaction Control System
RMS	Remote Manipulator System
RPM	Revolutions Per Minute
S	Entropy
S/C	Superconducting
SFHe	Superfluid Helium
SFHT	Superfluid Helium Tanker
SHOOT	Superfluid Helium On-Orbit Transfer
SIRTF	Space Infrared Telescope Facility
SMCH	Standard Mixed Cargo Harness
SOW	Statement of Work
SRD	System Requirements Document
STICCRS	SIRTF Telescope Instrument and Cryogen Changeout Replenishment Study
STS	Space Transportation System
T	Temperature
TAO	Thermal Acoustic Oscillation
TBD	To Be Determined
TBS	To Be Supplied
TDRSS	Tracking and Data Relay Satellite System
TM	Thermomechanical
TPMS	Temperature and Pressure Monitoring System
TVS	Thermodynamic Vent System
USL	United States Laboratory

Acronym	Definition
V	Specific Volume
VCS	Vapor-Cooled Shields
VLPS	Vapor-Liquid Phase Separator
VPF	Vertical Processing Facility

1.0 INTRODUCTION

Replenishment of superfluid helium (SFHe) offers the potential of extending the on-orbit life of observatories, satellite instruments, sensors and laboratories which operate in the 2K temperature regime. We have continued over the past 6 months to conceptually define a superfluid helium tanker (SFHT) for accomplishing on-orbit resupply. This report provides a top-level summary of the major program conclusions, analyses/trade study results, recommended fluid, structural, thermal and avionic subsystem conceptual designs and operational considerations for both STS and ELV launch of the SFHT. We have also addressed programmatic issues such as technology development needs and a program plan for SFHT development through delivery of a tanker to NASA-KSC in 1997.

The results presented herein are those of Task 3 - Conceptual SFHT System Design (Section 3.0), Task 4 - Commonality Assessment and Technology Development Recommendations (Section 4.0), and Task 5 - Program Plan for SFHT Development (Section 5.0). The results of Tasks 4 and 5 are in final iteration.

We have considered a mixed-fleet approach to SFHT utilization. Our 6000 liter tanker concept, shown isometrically in Figure 1.1, is compatible with launch on both the STS and Delta, Atlas, Titan III and Titan IV expendable launch vehicles (ELVs). The tanker will also permit servicing from the Shuttle cargo bay, in-situ when attached to the OMV and carried to the user spacecraft, and as a depot at Space Station. Our conceptual design approaches for all the subsystems are presented in this document.

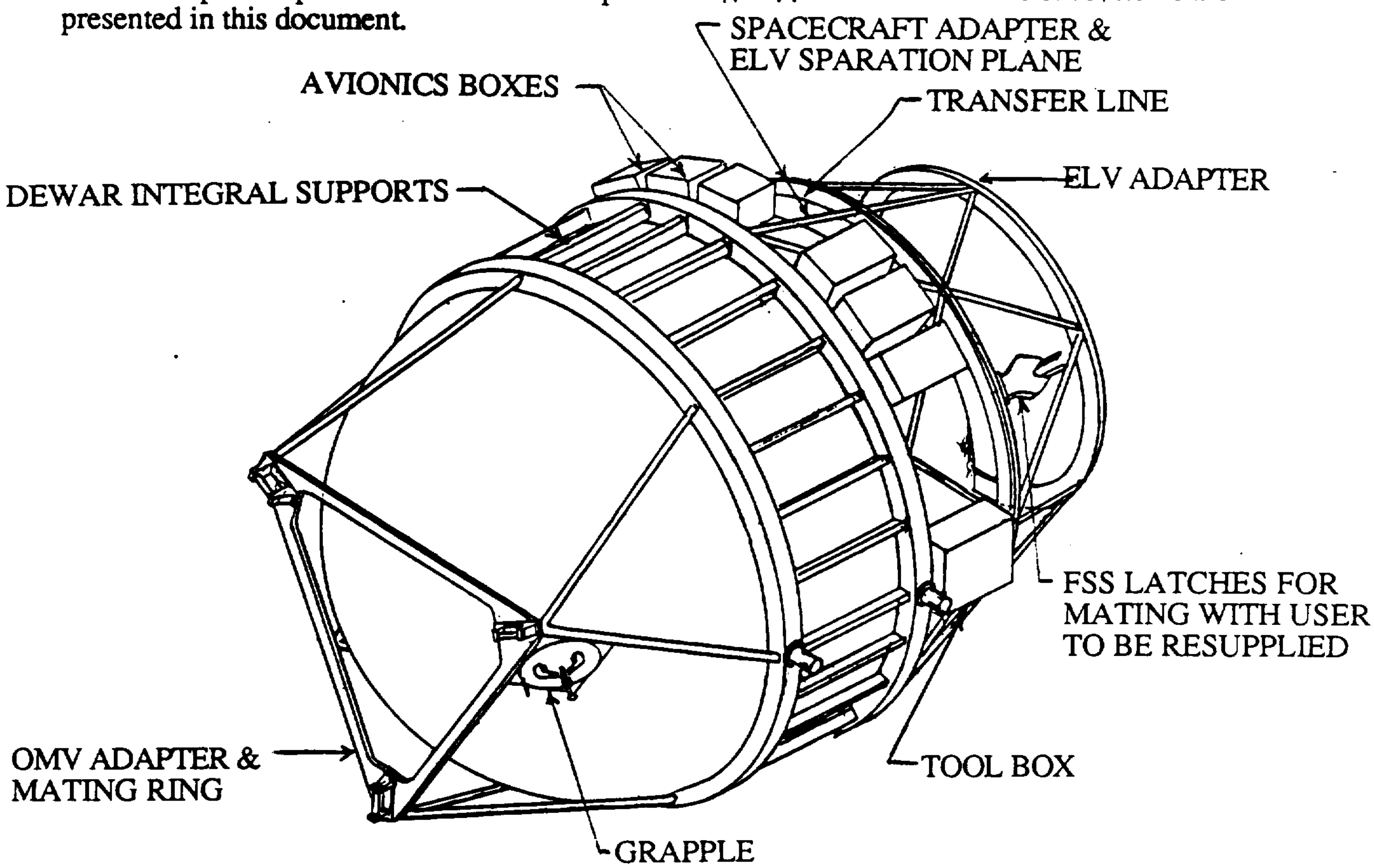


Figure 1.1 Superfluid Helium Tanker Concept

2.0 DESIGN GUIDELINES AND GROUNDRULES (UPDATE)

The objectives of the superfluid helium tanker study are to define requirements, prepare a conceptual superfluid helium tanker design, conduct a commonality assessment and identify recommended technology deficiencies and prepare a development plan and cost estimate. The first two tasks were to collect the user requirements and prepare a fluid subsystem conceptual design to be used for interaction with other tanker subsystems in Task 3. These results were documented in our Interim Progress Report (Reference 2.1).

Following our Interim Program Review at NASA-JSC, we updated our design guidelines and assumptions. Those previously defined in our Interim Report are still valid; we added to and expanded these based on comments made at the review and per items tabulated by NASA-JSC in the minutes of the review. We are still using the baseline SFHT requirements in the contract SOW, and the System Requirement Document Attachment A of the SOW as our basis. The following design guideline updates and additions further clarify and bound our Task 3 conceptual design effort:

1. A reduced set of resupply customers shall be used; SIRTF, AXAF, Astromag, MMPS/CPPF and LPE. The updated user database for these is presented in Table 2.1.

2. STS considered prime resupply site, but SFHT design to be compatible with use on Space Station for 9 month orbital stay and station venting requirements.

3. SFHT design impacts and capability should be considered if Space Station on-orbit storage time were to be increased to 12 months.

4. Baseline ground hold capability shall be compatible with closing orbiter cargo bay doors ten days prior to launch (this was original SOW requirement, but we had discussed the possibility with NASA-KSC of reducing this to 4 days).

5. Identify required GSE for emergency venting on the ground prior to installation into Orbiter.

6. A "generic" orbiter inert gas vent will exist in at least one of the orbiters. Vent line sizing and thermal analysis shall be performed to establish SFHT requirements for this generic line.

7. Re-assess need for SFHT servicing capability in both horizontal and vertical positions.

8. Emphasis on SFHT avionics should be placed on tanker-to-user functionality, rather than tanker-to-host (i.e., Orbiter or station). Policy on orbiter payload control by the GPC is indeterminant at this time.

9. Address the weight and complexity impacts to both the user and SFHT of the allocation of servicing hardware to either. The launch cost is only paid once if incorporated into user; complexity probably should be maintained on tanker to permit maintenance.

10. Task 4 commonality assessment should be limited to identification of possible areas of commonality with other cryogen tankers, as opposed to analytical studies of system capabilities and designs.

11. Flow gauging accuracy of ±5 percent and mass gauging accuracy of ±3 percent.

A study flow of the three tasks whose results are documented in this report is presented in Figure 2.1. We have taken a systems approach to subsystem design trades and interactions of the various subsystems to be sure that one subsystem is not penalized relative to the others, and that the fluid (superfluid helium) subsystem is properly integrated with structure, thermal, and avionics subsystems.

Table 2.1 SFHe User Database - Reduced User Complement

User	Helium Volume (liters)	Service Interval (days)	Service Time (days)	Orbit (km)	Launch Date	Mission Lifetime (years)
SIRTF	4000	730	3 to 14	700	1997	6 to 12
AXAF	200-400	730	TBD	600	1996	8
ASTROMAG	3100	730	TBD	at SS	1998	6 to 8
MMPS/CPPF	200	30-90	1 to 7	at SS	1994	5

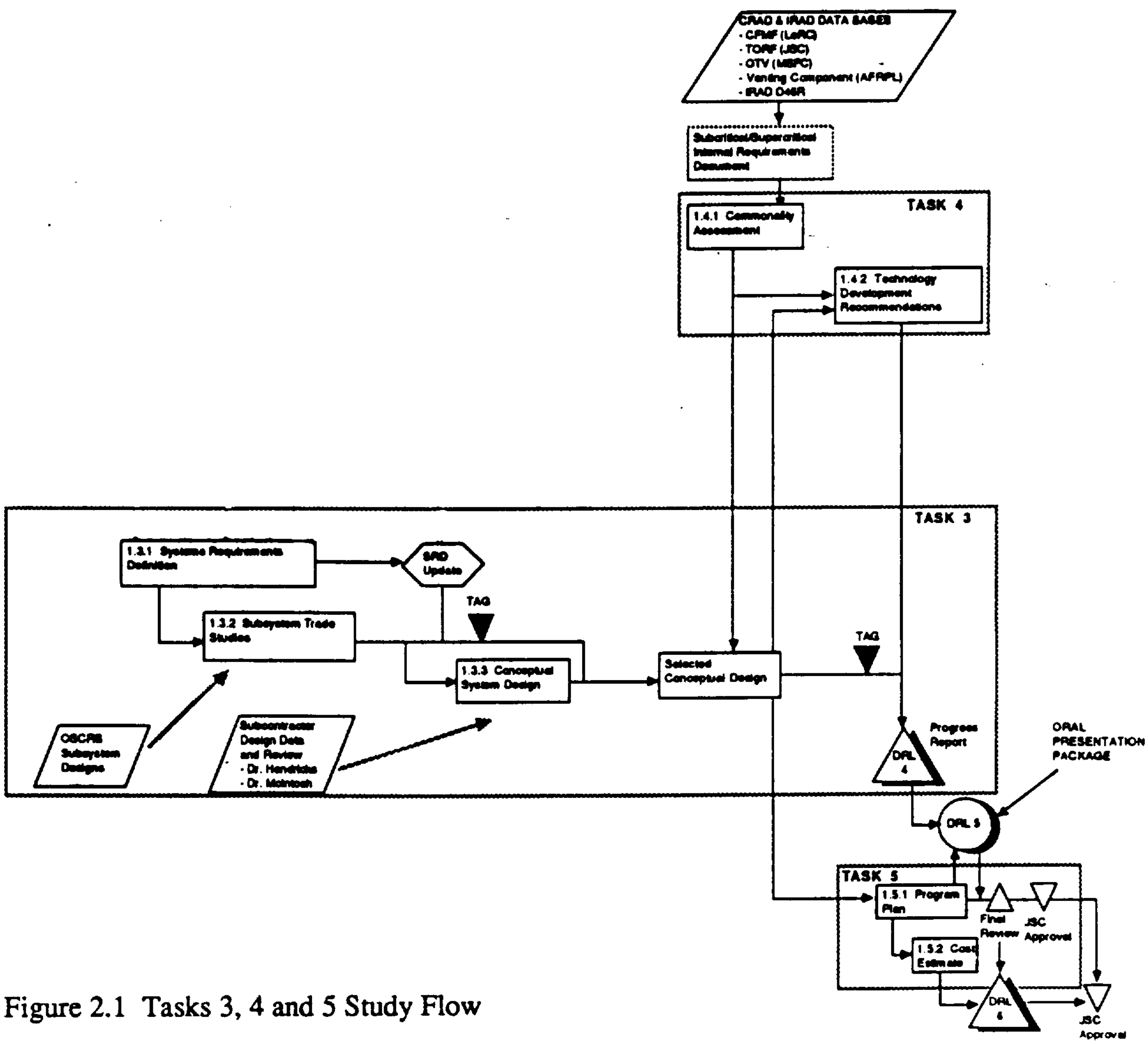


Figure 2.1 Tasks 3, 4 and 5 Study Flow

3.0 TASK 3 - CONCEPTUAL SFHT SYSTEM DESIGN

3.1 SFHT SYSTEM DESIGN

3.1.1 Tanker Optimization

3.1.1.1 Fluid Storage Sizing Trades - Trade studies were performed previously as part of Task 2 to optimize the capacity of the SFHT fluid system based on the user requirements. This section presents a summary of an update of these trades performed during Task 3. The reduced user complement that we identified during Task 2 was again used as the reference set with updated program start and launch dates, as presented in Table 2.1. The SFHT manifest model, also developed as part of Task 2, was redone using these requirements and is given in Figure 3.1. As shown, eight flights of the 6000 liter capacity SFHT are required to satisfy the users if all are resupplied from the Space Station. If SIRTF is resupplied from the STS (currently the baseline), then nine total flights are required: four in the STS for SIRTF and five to Space Station for the remaining users.

Currently, both SIRTF and Astromag prefer to be serviced while helium is still on-board. In the case of SIRTF, it is preferred not to allow the instruments to warm-up once they have reached helium temperatures. For Astromag, it is also desired to service with helium remaining to avoid having to cool the large magnets back down to operating temperatures thereby minimizing helium usage (Reference 3.1). Experiments mounted in the U. S. Laboratory, (MMPF/CPPF and Lambda Point Facility) are easily accessible and it should be possible to schedule refilling of these experiments while cold. A sensitivity analysis was previously performed as part of Task 1 to determine the impact on the flight frequency if some or all of the users required chilldown as well as resupply . The general trend was that as the resupply frequency and the amount of helium required increased, a larger capacity SFHT would be more efficient provided that all servicing was done at one location (i.e. Space Station) where the SFHT could serve as a general supply depot for all users. For example, if all of the users were resupplied warm, thirteen flights of the 6000 liter SFHT would be required during a ten year period compared to eight flights of a 15000 liter tanker. Offloading of a large capacity tanker for a cold SIRTF resupply from the STS, however, would eliminate the advantage in mass fraction possible with the larger tanker. Using the 11750 liter tanker design from the BASD STICCR Study (Reference 3.2), the fully loaded tanker has a mass fraction of 0.36. When offloaded to 5500 liters for a cold SIRTF resupply, the mass fraction is lowered to 0.21. Therefore, an intermediate size tanker appears to offer the best compromise to perform all of the planned resupplies from different locations.

A comparison of the on-orbit boiloff losses for tankers of various sizes was also performed in Task 2. This analysis was redone using more representative boiloff losses (approximately 1 1/2 percent per month), accounting for the smaller surface area-to-volume ratios for the larger capacity tankers. Representative results are shown in Figure 3.2, which compares cumulative boiloff losses against cumulative user requirements for the reference user complement considering a 6000 liter SFHT and a 15000 liter SFHT. As shown, the larger capacity SFHT results in approximately 21500 liters of helium lost overboard compared to 11700 liters for the 6000 liter tanker even though the larger tanker's geometry is more thermally optimized. Ideally the user requirement and the amount of helium transported to orbit should be as close as possible to minimize losses.

Based on the above results, we feel that a 6000 liter capacity SFHT, derived from the Task 1 trades, satisfies the mission requirements in the most efficient manner. It is sufficient in size to resupply SIRTF under normal conditions without an undue penalty for the smaller users. Also, this capacity makes the option of packaging into smaller ELV payload fairings a practical option, as discussed in the next section. However, an important conclusion reached during the sizing studies was that the optimum SFHT size is heavily dependent on the user requirements in terms of both user capacity and

	Capacity of	1260		Capacity of	
	Tanker 1 (l):			Tanker 2 (l):	6000
Quarter	Helium	# ofTanker 1	# of Tanker 2	Helium in	
	Required, liters	Flown	Flown	Tanker (l)	
1997	0			0	
	200		1	5493	
	200			4986	
	200			4479	
1998	200			3972	
	3700		1	5965	
	200			5458	
	200			4951	
1999	200			4444	
	200			3937	
	200			3430	
	4200		1	4923	
2000	200			4416	
	3700			409	
	200		1	5902	
	200			5395	
2001	200			4887	
	200			4380	
	200			3873	
	4200		1	5366	
2002	0			5059	
	3500			1252	
	0			945	
	0			638	
2003	0			331	
	0			24	
	0			0	
	4000		1	1693	
2004	0			1386	
	3500		1	3579	
	0			3272	
	0			2965	
2005	0			2658	
	0			2351	
	0			2044	
	4000		1	3737	
2006	0			3430	
	400			2723	
	0			2416	
	0			2109	
TOTALS	34200		8		

Figure 3.1 SFHT Manifest to Meet Reference User Complement Requirements

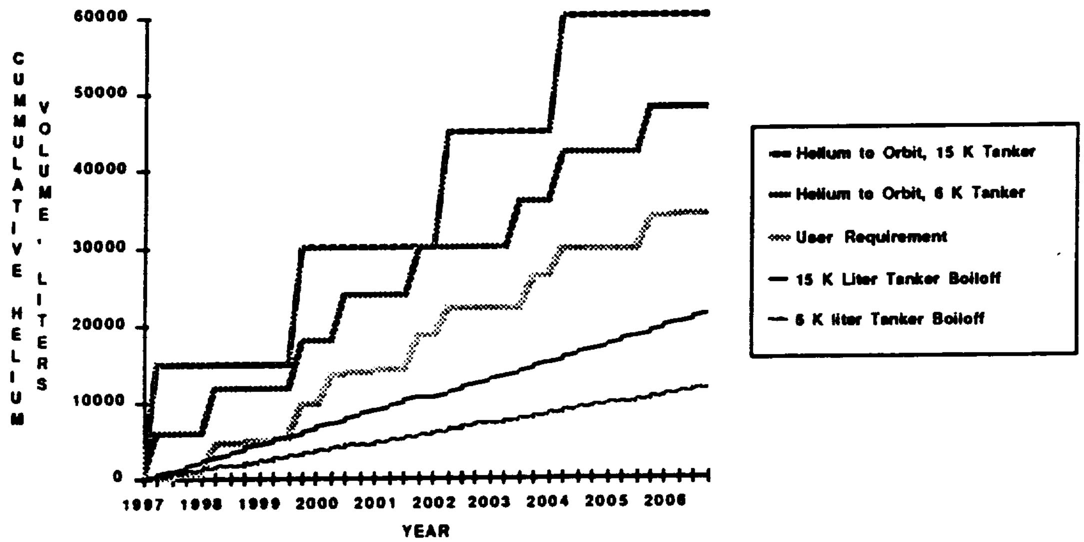


Figure 3.2 Tanker Capacity Sensitivity to Boiloff Losses in Meeting the Reference User Complement Resupply Scenario

resupply frequency. Therefore, it is recommended that the sizing issue continue to be readdressed as the user requirements mature.

3.1.1.2 Launch Vehicle Options - An objective of this study was to determine design impacts to the SFHT of launch both on an ELV and the Shuttle. A mixed manifesting approach, using both ELV's and the Shuttle, is being considered for Space Station logistics resupply (Reference 3.3). Early in Task 2, we established the requirement to examine all ELV's, not just the Titan IV. This was done to ensure that compatibility with a maximum number of ELV's was examined. Designing payloads such as the SFHT to accommodate both ELV and Shuttle launch must necessarily impose some compromise in the design. Specifically, the dual launch requirement involves compromising the SFHT's length since most ELV payload fairings are smaller than the 15 foot diameter of the Shuttle cargo bay.

A review was made of existing ELV's to determine parameters such as payload lift capability, fairing size, and cost (References 3.4 - 3.7). The results are shown in Table 3.1 along with comparable data for the Shuttle. Published launch costs for all of the vehicles tend to vary widely since they usually are tied to procurement rates. However, the launch costs shown for the ELVs were provided to NASA LeRC by the ELV contractors (Reference 3.8). A wide range of fairing and payload adapter diameters are available. For example, the Titan III provides payload adapters in eleven different diameters. Of the available payload fairings, the Delta II fairing has the smallest diameter (10 feet O.D.) and would present the most difficult packaging problem for sizes exceeding approximately 5000 liters.

Table 3.1 Launch Vehicle Comparison

PARAMETER	DELTA II	ATLAS/CENTAUR	TITAN III	TITAN IV	STS
LAUNCH COST	$45M*	$59M*	$110M*	$160M**	$140
PAYLOAD TO 250 NM ORBIT, LBS	8000 (6920) 10000 (7920)	10500	29500	~39000	48000***
DOLLARS PER POUND (TO ABOVE ORBIT)	5625	5619	3729	4103	2917
PAYLOAD FAIRING I.D., IN.	110	115,143.7	143.7	180.0	180.0
PAYLOAD ADAPTER INTERFACE DIAMETER, IN.	32.5,60	32.5	32.8-70.0	111.77	N/A

*FROM DATA SUPPLIED BY NASA LeRC FOR COLD-SAT PROGRAM
** HARDWARE COSTS ONLY, NO MISSION SUPPORT/INTEGRATION INCLUDED
***WITH PERFORMANCE UPGRADES

A benefit of the selection of the smaller capacity 6000 liter SFHT is that it provides easier packaging within the smaller payload fairings. Designing the SFHT to a nine foot diameter to package within the Delta II payload fairing dynamic envelope results in a slightly longer length tanker which penalizes it somewhat for a Shuttle launch. This penalty is minimized, however, by the smaller capacity tanker. Therefore, due to the selection of the 6000 liter SFHT, we chose to maximize compatibility and design the SFHT to fit within the Delta II faring. The length penalty associated with this design diameter for a Shuttle launch is 2-3 feet. The packaging of the nine foot diameter, 6000 liter SFHT in the various ELV fairings is shown in Figure 3.3 for comparison. The SFHT uses most of the payload fairing volumes for the Delta II and Atlas/Centaur vehicles. For the Titan vehicles however, significant payload weight and volume margins remain, indicating that the SFHT would be part of a multiple payload launch for these vehicles.

A study was initiated to determine if any launch cost benefits are provided by designing for compatibility with all of the existing ELV's rather than just the Titan IV and Shuttle. The manifesting model developed during Task 2 determined that 9 flights of the SFHT would be required if resupply missions were performed from both the Shuttle cargo bay and the Space Station. It was assumed that all SIRTF resupply missions would be performed from the Shuttle and that AXAF, Astromag, and MMPF/CPPF servicing be done from the Station, resulting in five flights to the Station. Launch costs for this scenario were calculated for each of the ELV's. Costs were computed by calculating the percentage of payload capacity used by the SFHT (assuming an SFHT wet weight of 6000 lbs) to a 250 nautical mile orbit and multiplying the launch cost presented in Table 3.1 by this percent. The results are presented in Figure 3.4 which shows the launch costs for all combinations of ELV and Shuttle launches. As shown, the mixed manifesting approach results in launch costs that are comparable to those of the Shuttle. Other benefits such as manifesting flexibility and the simplifications of ground operations of an ELV launch (discussed in Section 3.3.1.2) are not included.

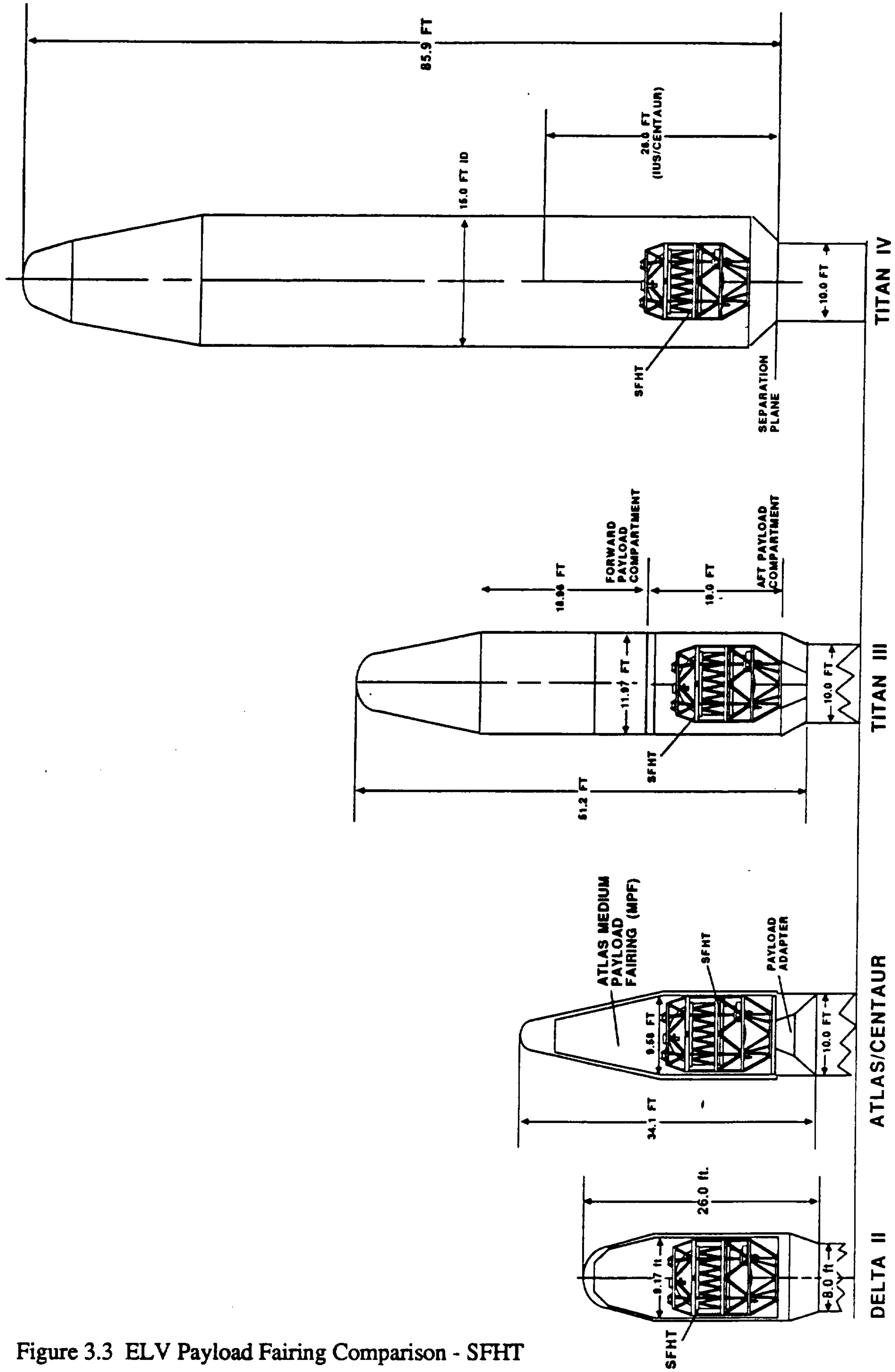


Figure 3.3 ELV Payload Fairing Comparison - SFHT

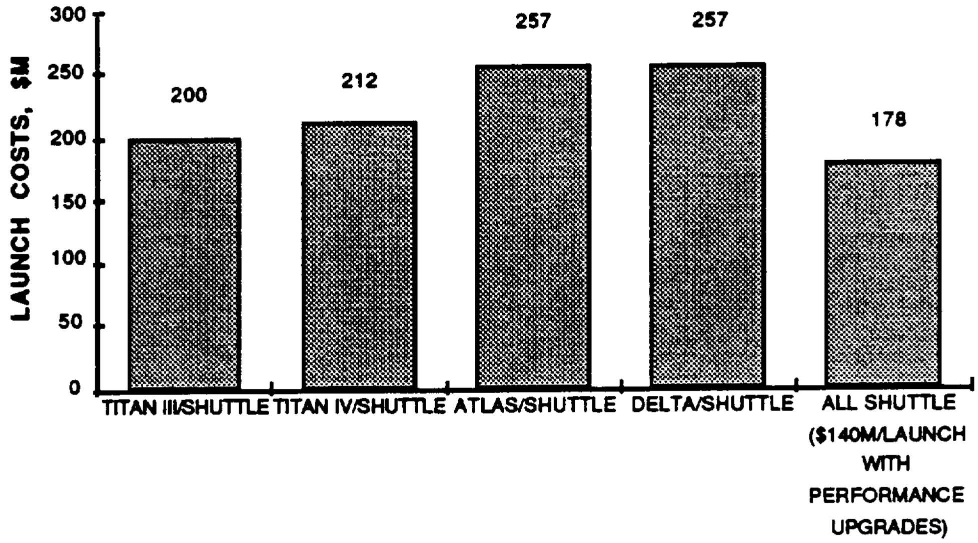


Figure 3.4 SFHT Launch Cost Comparison for Mixed Fleet Manifesting

3.1.2 Operations

3.1.2.1 Interface Requirements -

SFHT/STS Interfaces - The STS can be both the launch vehicle and the base of resupply operations for the SFHT. Interfaces required between the SFHT and the STS are structural, electrical, and fluid. The SFHT can be launched in the STS, removed on-orbit, and then replaced in the cargo bay for return to the ground. Therefore, these interfaces must be mateable and demateable on-orbit.

The interfaces between the SFHT and the STS are depicted in Figure 3.5. Structural interfaces will consist of the standard trunnion and keel fittings located on the SFHT cradle. An active keel mechanism is required to permit berthing and unberthing of the SFHT while on-orbit. Also, a minimum of two standard RMS grapple fixtures will be required to permit the Shuttle RMS to perform the berthing/unberthing and to pass the SFHT to the Space Station MRMS. The electrical interface between the SFHT and the Shuttle will be used to provide power, monitoring, and control to the tanker. Details of the function of the interface can be found in Section 3.1.6. This interface will also require a mateable/demateable electrical coupler for those missions where the Shuttle is serving only as the launch vehicle and not the base of operations of the SFHT.

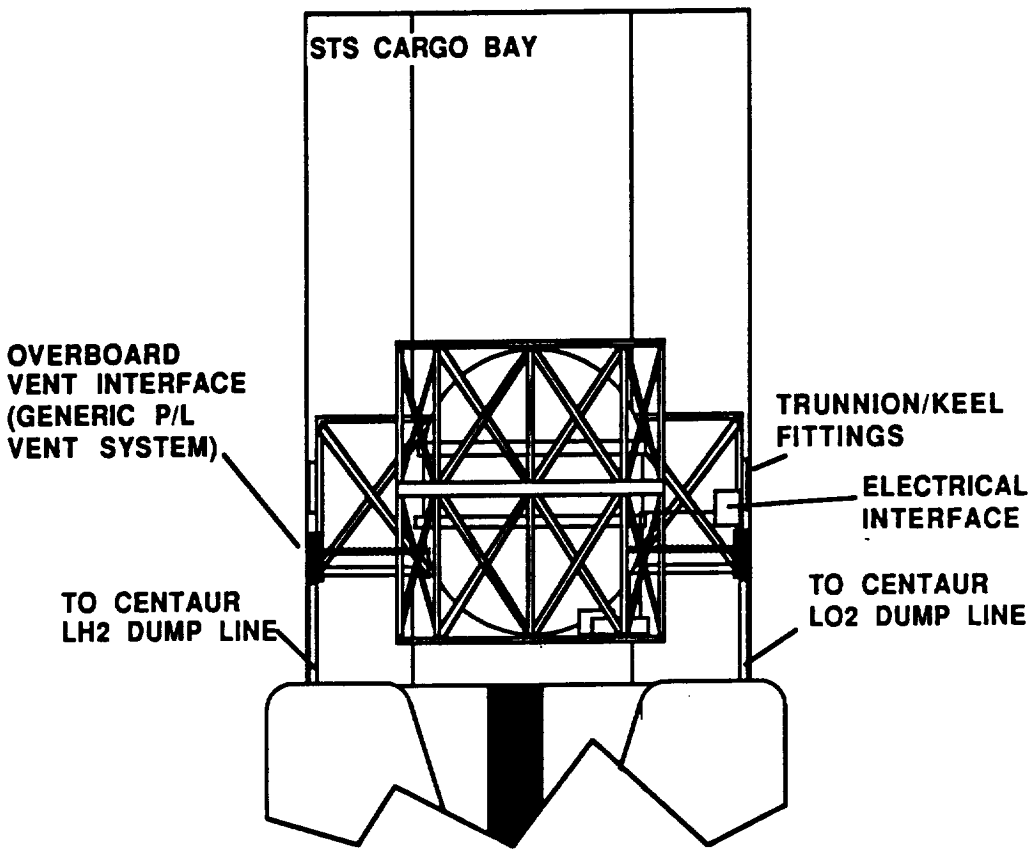


Figure 3.5 SFHT Mounted in the STS Cargo Bay

Early in Task 2, the need for an emergency overboard vent interface between the SFHT and the Shuttle was identified to handle a catastrophic loss of vacuum in the Dewar. The large mass flow rates resulting from such a failure mode (~2 lbs/second) coupled with the cold temperature of the vent gas require an overboard dump at all times when the SFHT is in the payload bay. The generic payload vent system being installed in all the Orbiters consists of a two inch diameter line running the length of the payload bay on either side (Reference 3.9). The two lines discharge overboard through the Centaur liquid hydrogen and liquid oxygen dump interfaces. The lines will be insulated to prevent the formation of liquid air during dumping of cryogenic fluids such as helium. In addition, the lines can be pressurized on the ground with nitrogen or helium gas and capped off to provide a positive pressure to prevent leakage of air. The SFHT would have two interfaces with this system, one on either side of the tanker to provide two independent paths for the emergency vent system. The interfaces would be located at the payload bay sill and mated in the Payload Changeout Room as the SFHT is placed in the cargo bay. These interfaces need to be demateable on-orbit, and mateable if the SFHT is returned to the bay with helium still on-board. If the SFHT is dry, then the interface need not be mated for return to the ground.

SFHT/Space Station Interfaces - The SFHT can be stored at the Space Station to perform periodic resupply of a variety of users. As discussed in Section 2.0, users at the Space Station will consist of experiments in the U.S. Laboratory, free flying payloads brought to the Station, and semi-permanent payloads attached to the truss assembly. Since the Servicing Facility, discussed in Section 3.1.2.3, is not currently part of the Space Station baseline configuration, interfaces were defined assuming the SFHT is attached to the truss assembly only. These interfaces, shown in Figure 3.6, consist of structural, electrical, and fluid interface.

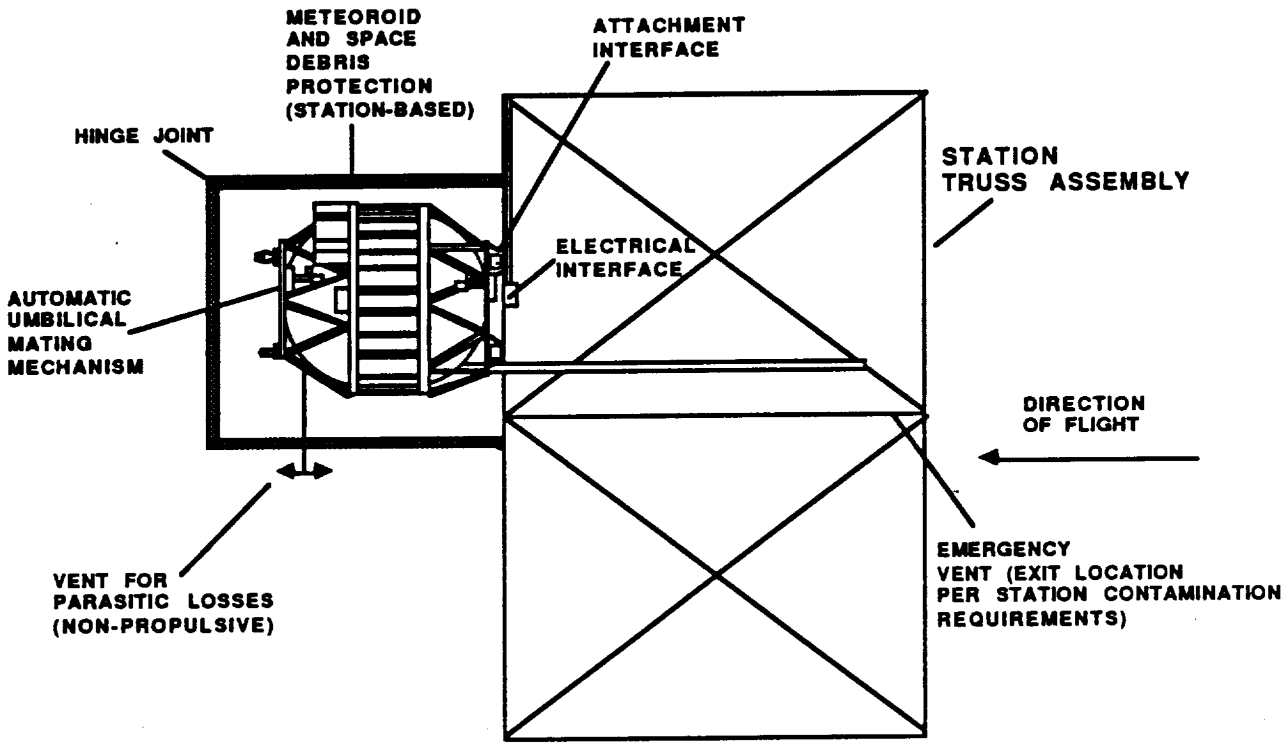


Figure 3.6 SFHT Attached to Space Station Truss Assembly

The SFHT would be attached to the truss assembly using a standard docking mechanism such as the FSS latches. If the SFHT is left in its transport cradle (see Section 3.1.5.1), then the SFHT could be attached to the truss via the trunnion and keel fittings. An additional structural interface requirement, although not directly a part of the SFHT structure, is for meteoroid and space debris protection. This protection is required since the SFHT may spend up to 12 months attached to the Station. The amount and configuration of this protection depends on the location of the SFHT on the Station and how much it is shielded by other elements of the Station. Regardless of the SFHT location, the debris protection would be left on the Station and not incorporated in the SFHT structure to save weight. The meteoroid and space debris protection would consist of an aluminum panel 0.03 inches to 0.075 inches thick configured with hinges to allow it to be folded away for SFHT removal or replacement.

Another SFHT/Station interface requirement is to provide shielding of potentially explosive containers to prevent their failure from propagating to other nearby structures or containers, or from endangering other Station elements such as the pressurized modules (Reference 3.10). This requirement could imply that shielding must be provided around the SFHT to contain fragments caused by a catastrophic failure of the Dewar. This requirement, however, would impose a substantial weight penalty. In order to satisfy this requirement, the possible failure modes of the SFHT Dewar were evaluated. Assuming that adequate meteoroid and debris protection is provided, then the SFHT Dewar could only explode if the Dewar guard vacuum was compromised by an internal leak. In this case, two-fault tolerant mechanical pressure relief is provided. In addition, the

Dewar would be designed to leak-before-burst criteria. Therefore, it is felt that the requirement for shielding could be satisfied by debris protection and mechanical pressure relief devices. However this hazard should be further addressed as the possible locations of the SFHT at the Space Station are better defined.

An electrical interface, described in Section 3.1.6, provides power, command, and data handling from the Space Station avionics. The Space Station avionics replaces the Shuttle Aft Flight Deck control system for controlling and monitoring the SFHT during all phases of its mission. This interface must also be mateable and demateable. An electrical interface between the SFHT and the Station MRMS would not be required unless it was desired to perform helium replenishment operations while attached to the MRMS. In this case, one fault tolerant command, data, and power would be provided to the SFHT by the MRMS.

As with the Shuttle, an emergency overboard vent interface is required to handle the loss of Dewar vacuum. This line must run from the SFHT storage location to a point where the discharge will not produce a hazard to either the crew or a Station element. Currently, waste gases from the Station will be discharged at the end of a stinger to reduce the contamination potential and to provide for reboost thrust. If it is determined that the emergency vent must discharge in this same area, the line length required would be approximately 100 feet. This long length would necessitate a line diameter of 2 inches or more in order to obtain a manageable pressure drop during the emergency vent. A more preferred approach would be to configure the emergency vent system with the minimum amount of line length required to direct discharge away from primary Station elements.

<u>SFHT/OMV Interfaces</u> - Coupling the SFHT and the OMV for transport in-orbit will require both structural and electrical interfaces. The OMV can provide payloads with three types of structural interfaces (Reference 3.11). The Three Point Docking Mechanism (TPDM) interfaces with standard FSS type latches and consists of three coordinated latches mounted on a structural ring, with redundant TV cameras, lights, and electrical umbilicals. The RMS Grapple Docking Mechanism interfaces with a standard RMS grapple fixture and incorporates three snare wires with a retracting mechanism, cameras and lights, and an integral electrical connector. Both of these interfaces are intended for orbital operations and are therefore limited in the amount of loads they can withstand. Payloads can be bolted to the front face of the OMV using a 135 inch diameter circular interface capable of a 10000 ft-lb cantilevered moment for a Shuttle launch. This bolted interface can be mated or demated by an EVA astronaut on-orbit. Capability to use this interface for an ELV launch, however, has not been examined and appears to be limited (Reference 3.12). Therefore, it appears that the SFHT cannot be physically mated to the OMV during an ELV launch.

In addition to a structural interface, an electrical interface for power and telemetry will be required. The OMV provides total power of 5 kwh to a payload with a 1 kw peak. A Fairchild data system is also available for payload use. The SFHT will also have to provide the necessary hardware to provide pass through of OMV utilities to a user spacecraft such as SIRTF. The SFHT/OMV electrical interface would be a part of the TPDM or RGDM mechanisms.

The SFHT/OMV interfaces are summarized in Figure 3.7. Additional equipment will be required by the SFHT to operate while attached to the OMV even though this equipment is not a direct physical interface with the OMV. A docking target visible to the camera package on the OMV's TPDM will be required to ease mating of the SFHT and OMV on-orbit. Once attached, a camera and light

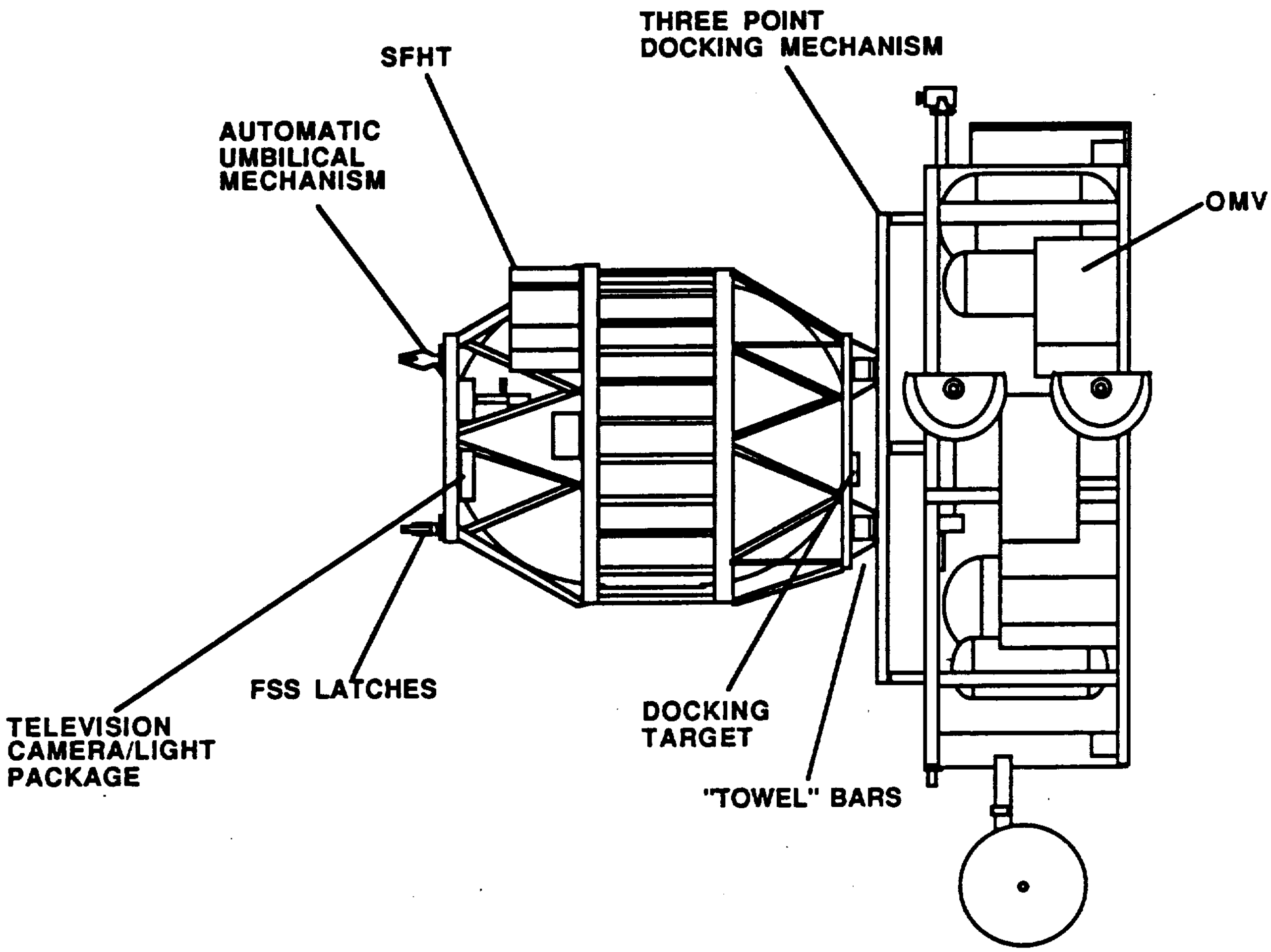


Figure 3.7 SFHT Mated to OMV for Transport to User Spacecraft for In-Situ Resupply

package attached to the front face of the SFHT would allow additional viewing for mating to a user spacecraft. An automatic coupler mating mechanism on the front face of the SFHT would also be required to mate fluid and electrical couplers to the user along with an FSS or similar interface to mate with the user spacecraft.

SFHT/ELV Interfaces - Launch of the SFHT on an ELV requires launch vehicle interfaces similar to those required for a Shuttle launch. Figure 3.8 shows the SFHT in a typical ELV payload fairing. An interface to the ELV payload adapter to react launch loads, and an electrical interface for power and telemetry, will be required. Additionally, interfaces with the GSE during the ground processing flow will require access holes in the ELV payload fairing to allow for helium servicing, power, and monitoring via the SFHT GSE. Also, as in the Shuttle launch case, vent interfaces with the fairing are required for both normal and emergency venting. These interfaces should be located to use the same ground service panel on the SFHT as during Shuttle launch processing. The SFHT/ELV structural interface is a deployable interface requiring the use of explosive bolts to allow the SFHT to be separated from the expended launch vehicle on-orbit.

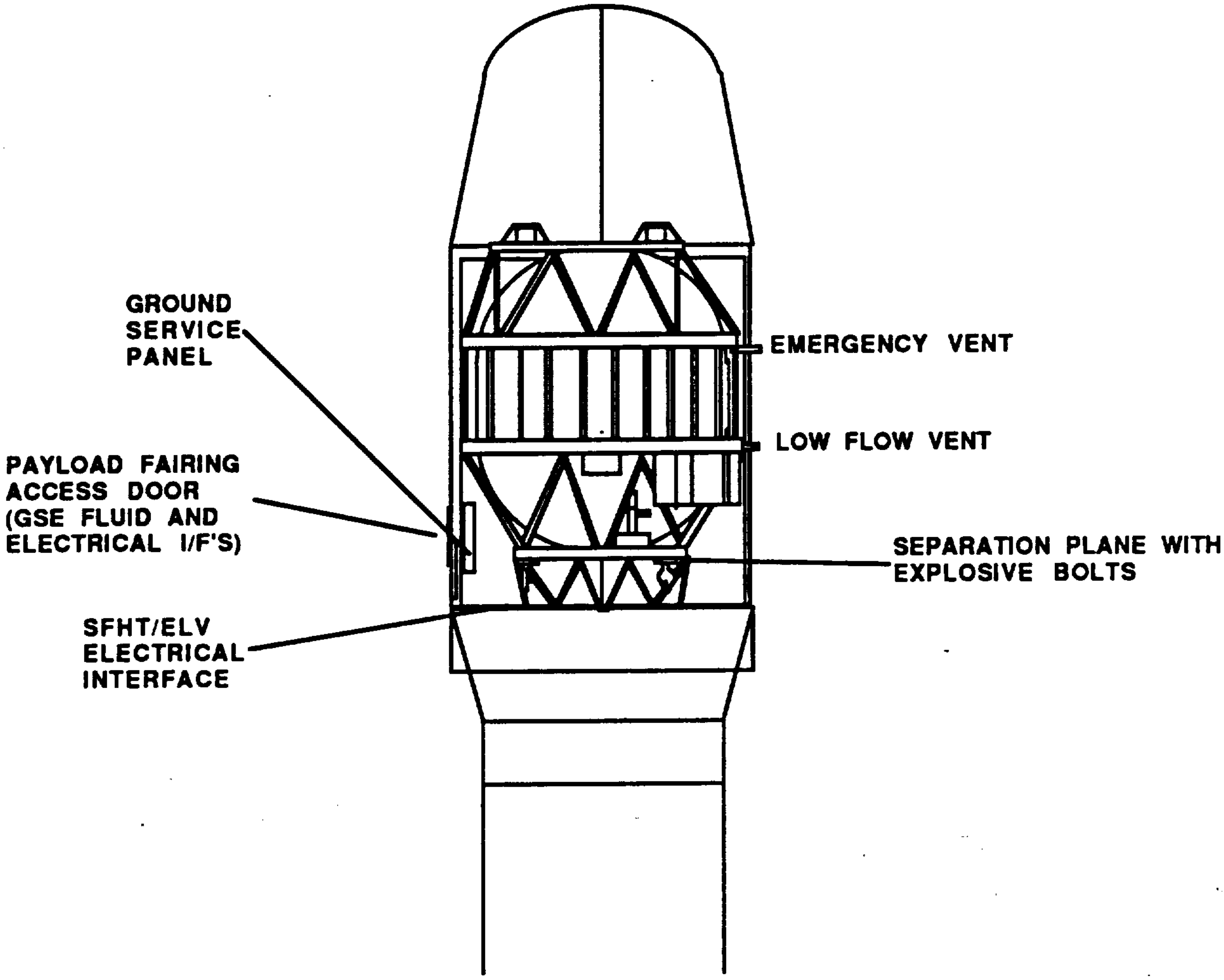


Figure 3.8 SFHT/ELV Interfaces for Delta II ELV

Automated versus Crew Operations Trade - An operational consideration associated with any on-orbit fluid resupply operation is the option of using EVA astronauts or an automated device to mate and demate the fluid and electrical couplers required to perform the transfer. In general, EVA operations are preferred when the automated option is too expensive, not versatile enough, not reliable enough for a particular critical operation, or not capable of performing the operation with existing technology. Automated operations should be considered when the operation is hazardous to the EVA crewmember, is less expensive than EVA, when the task required to be performed is routine and repetitive, the operation requires the application of precise and extreme forces or a man is not in space at the resupply location.

In the OSCRS studies, resupply of the Gamma Ray Observatory (GRO) using an EVA crewmember was the baseline. Manual mating of helium couplers will be an integral part of the SHOOT experiment and will demonstrate the ability of the EVA crewmember to handle the helium couplers and vacuum jacketed flex lines. With this background, EVA mating of couplers required for the SFHT will be demonstrated. There are, however, advantages to automatic operations specific to superfluid helium transfer. The long flex lines required (on the order of 20 feet for an STS-based SIRTF resupply operation - see Section 3.1.2.3) result in a large heat leak and pressure drop. For example, the flex lines add as much as 3 watts heat input each, and can weigh as much as 3 pounds per foot if they are vacuum jacketed. An automated coupler mating mechanism would weight approximately 40 pounds (excluding the couplers) based on current designs. Automatic resupply operations would allow the user spacecraft to be mated directly to the SFHT structure, minimizing the transfer line length. Additionally, this would provide commonality of SFHT operations regardless of where the resupply operation would take place. Additionally, there are potential hazards associated with the handling of long flex lines in zero-g. Line tethering would be required to avoid inadvertent movement of the line. In addition, the EVA flex lines would need to be purged prior to disconnecting, adding time to the transfer sequence.

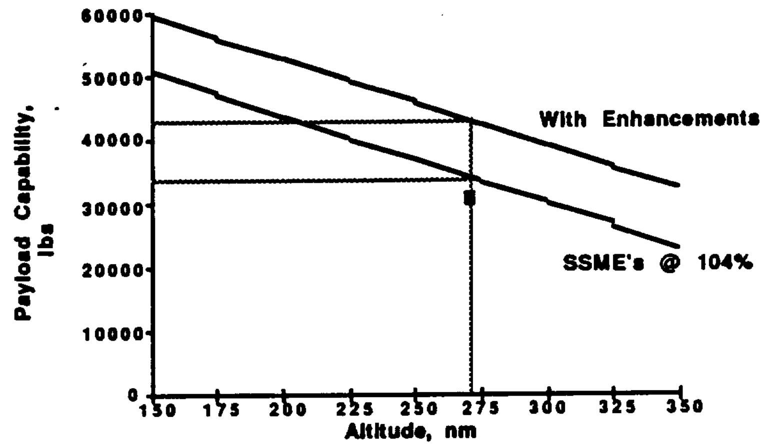
Automatic resupply operations would require an automatic coupler mating mechanism on both the SFHT and the user spacecraft. The active side of the coupler mating mechanism would be located on the SFHT and the passive side on the user spacecraft. The active side of the mechanism would be heavier and incorporating it onto the user spacecraft side would save launch costs. However, since the SFHT is returned to the ground frequently, placing the active side of the mechanism, critical to mission success, on the SFHT would allow access for maintenance and enhance reliability. Once the SFHT and the user spacecraft are physically docked, the automatic coupler mechanism would engage the fluid and electrical couplers allowing a minimum line length to be used. Based on these considerations, therefore, it is strongly recommended that automatic resupply operations be encouraged for future users of the SFHT, although the ability to perform EVA operations be included in the tanker design.

3.1.2.3 On-Orbit Resupply Operations - The SFHT Systems Requirements Document (SRD) defines the types of resupply operations that the SFHT must perform. Helium replenishment operations can take place from the Orbiter cargo bay, Space Station, and while attached to the OMV. Satisfying each of these cases requires a thorough definition of the operations for each to determine what hardware and design features are required. The following paragraphs discuss the operations required to satisfy the SRD requirements and define the configuration impacts to the SFHT. In developing these operational scenarios, SIRTF was used as a representative user spacecraft since data on its configuration is readily available. Discussions with NASA Ames Research personnel were conducted to obtain the latest data on the SIRTF configuration and mission. The baseline resupply/servicing concept is for Shuttle-based resupply. No on-orbit instrument change-out is planned and it is desirable to always resupply SIRTF when helium is remaining to avoid warming up the instruments. Resupply of a warm SIRTF therefore is a contingency operation only.

Resupply from Orbiter Cargo Bay - Resupply from the Orbiter cargo bay is considered the baseline operational case for the SFHT. The Space Station configuration does not include the Servicing Facility; therefore, the current plans are to perform servicing from the Orbiter. The baseline SIRTF resupply mission calls for a dedicated Shuttle flight. The Orbiter would transport the SFHT, an A' cradle, and an OMV to a 500 km orbit. The OMV would then be used to retrieve the SIRTF from its 900 km orbit and transport it to the Shuttle.

The combined weight of the fueled OMV, A' Cradle, and the SFHT is summarized in the table accompanying Figure 3.9. A plot of Shuttle payload capability versus altitude with the SSME's at 104% power and with performance enhancements is also shown in Figure 3.9. The payload weight required for the STS-based SIRTF resupply mission is highlighted in the figure and shows that ~90% of the Shuttle payload capability is required for the mission for the 104% power case and ~70% for the performance enhancement case. Use of a larger tanker or the requirement to launch two of the 6000 liter SFHT's to perform a resupply of a warm SIRTF would require the performance enhancements, using 90% of the payload capability.

Servicing of the SIRTF begins by placing it in the A' cradle. EVA astronauts would then connect and disconnect the SFHT fluid and electrical couplers to SIRTF. The configuration for these operations is shown in Figure 3.10. Orientation of the SIRTF in the cargo bay is not critical except that it is desirable to keep the telescope opening pointing away from the direction of flight to minimize contamination. The SIRTF could be rotated down into the cargo bay using the A' cradle to



ITEM	WEIGHT (LBS)
A' CRADLE	4906
OMV	18304
SFHT (6000 L)	6800
TOTAL	30010

Figure 3.9 STS Payload Assessment for SIRTF Resupply Mission

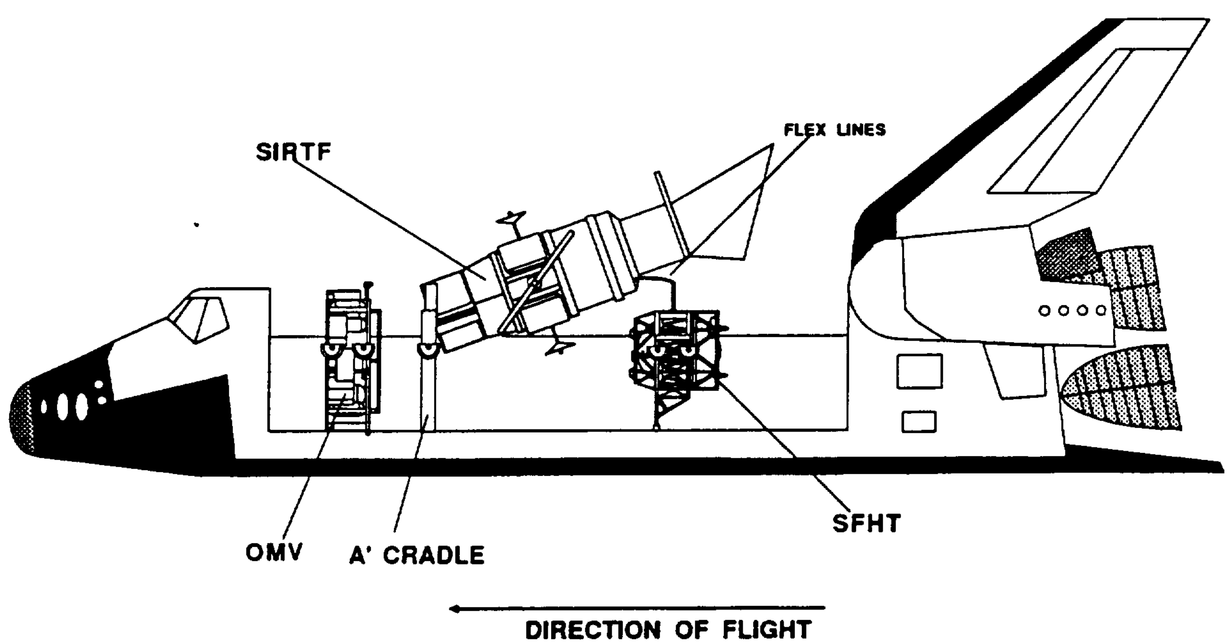


Figure 3.10 Manual Resupply of SIRTF in Cargo Bay

minimize the distance between it and the SFHT. This helps to minimize the required length of the flex lines. The line length is estimated to be approximately 20 feet to manually resupply SIRTF in the bay. To replenish the SIRTF without using EVA, the SIRTF would be directly attached to the SFHT and the fluid and electrical couplers mated by an automatic coupler mating mechanism, as shown in Figure 3.11. Even though EVA astronauts would be required to perform ORU changeout on the SIRTF, automatic resupply would provide benefits for the helium transfer operation by eliminating the long transfer lines and their associated flow losses and heat leak.

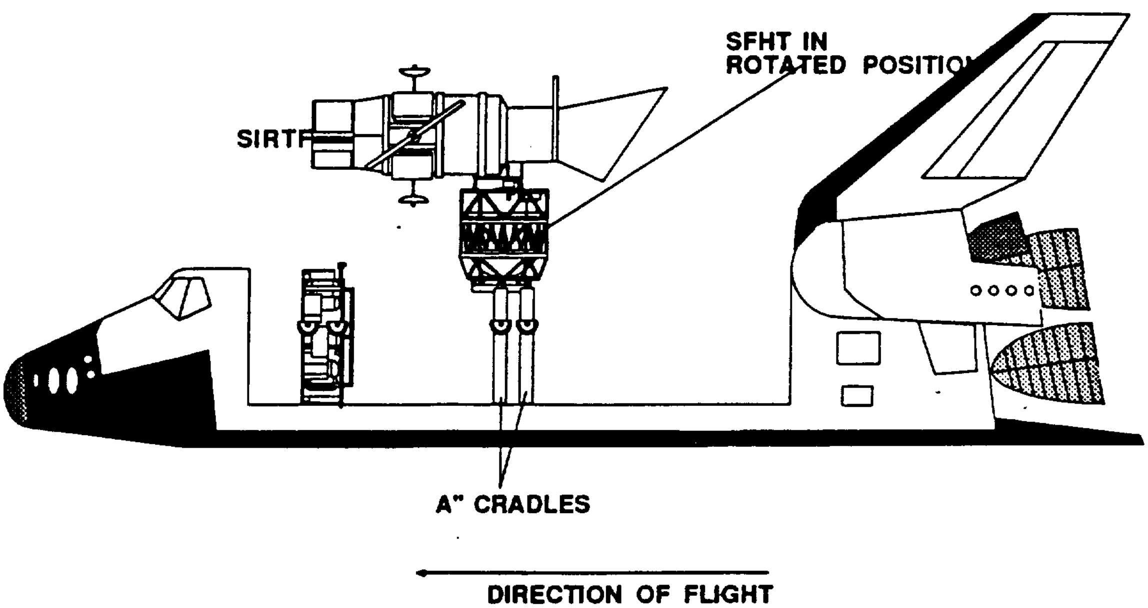


Figure 3.11 Automatic Resupply of SIRTF in Cargo Bay

Resupply at the Space Station - Replenishment of superfluid at the Space Station will be required for several planned attached payloads and experiments located inside the U.S. Laboratory Module. Additionally, servicing of the large observatories such as AXAF and SIRTF could also be performed. The frequency of resupply for the laboratory experiments (30 to 90 days) requires that the SFHT be located at the Station as a semi-permanent supply depot. The drawback to this approach, unlike tankers of storable propellants, is that the continuous boiloff from the SFHT cannot be recovered without adding significant hardware. Therefore, minimization of the boiloff becomes a key driver for the SFHT when it is Station-based.

Resupply operations at the Station can be performed with the SFHT on the truss assembly or with the SFHT in the Servicing Facility when it is in place. The Servicing Facility, shown in Figure 3.12, is an unpressurized structure attached to the transverse boom adjacent to the pressurized modules. The main elements include the Service Bay Enclosure, consisting of four telescoping thermal contamination barriers, the Service Track Assembly, a keel-mounted rail structure that supports Facility equipment such as fluid tankers, the Servicing Facility Manipulator, a track-mounted remote manipulator that is capable of reaching payloads in the Orbiter cargo bay and anywhere within the Servicing Facility, and the Universal Payload Adapter, an attachment device able to mate with grapple fixtures, FSS latches, and trunnion fittings.

Before the Servicing Facility is in place, the SFHT will be stored attached to the truss assembly. As discussed in Section 3.1.2.1, this storage location will require meteoroid and space debris protection plus fluid and electrical umbilcal connections. The most frequent resupply operations (at 30-90 day intervals) will involve experiments such as the MMPF/CPPF and Lambda Point Facility located

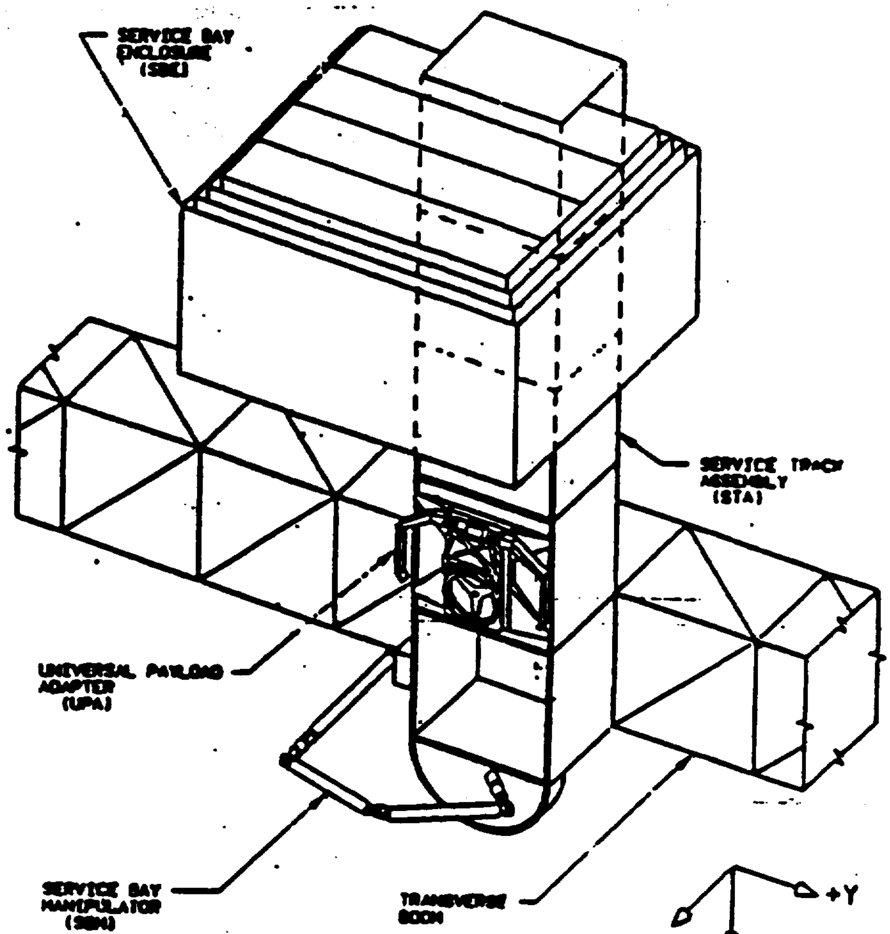


Figure 3.12 Space Station Servicing Facility

inside the U.S. Laboratory module. Therefore, it would be preferrable to locate the SFHT close to the U.S. Laboratory to minimize transfer line lengths and movement of the SFHT, provided that the emergency and normal vent exits are located in acceptable locations. the SFHT could be attached to the truss assembly near the U.S. Laboratory with a transfer line running to an interface located inside the pressurized area, as shown in Figure 3.13. If locating the SFHT close to the pressurized modules proves to be unacceptable due to safety or geometrical constraints, then the SFHT would have to be tranported to the U.S. Laboratory from an alternate truss storage location using the MRMS.

Servicing of larger users such as the AXAF and SIRTF would require a servicing area on the truss assembly with enough room to accommodate both the SFHT and the user spacecraft. The user could be attached to the truss with flex lines connecting it with the tanker or it could be attached directly to the SFHT interface as would be done during an in-situ resupply operation (see Figure 3.14). Servicing of Astromag would involve moving the SFHT to Astromag's location provided that the necessary utility connections are available at the Astromag location. An aleternate would be to leave the SFHT attached to the MRMS for power and data handling.

<u>Remote Resupply Operations</u> - One of the design requirements for the SFHT is that it be capable of resupplying helium to a user at a remote orbital location. Such operations would be performed while the SFHT is attached to the OMV. This requires the SFHT to incorporate structural and utility connections for attaching to both the OMV and the user spacecraft.

Interfaces with the OMV were previously discussed in Section 3.1.2.1. In addition to these interfaces, the SFHT would require a mechanism to dock to the user spacecraft and an automatic coupler mating mechanism to attach the fluid and electrical couplers. A concept for replenishing SIRTF with helium in-situ is shown in Figure 3.15. The front face of the SFHT would be

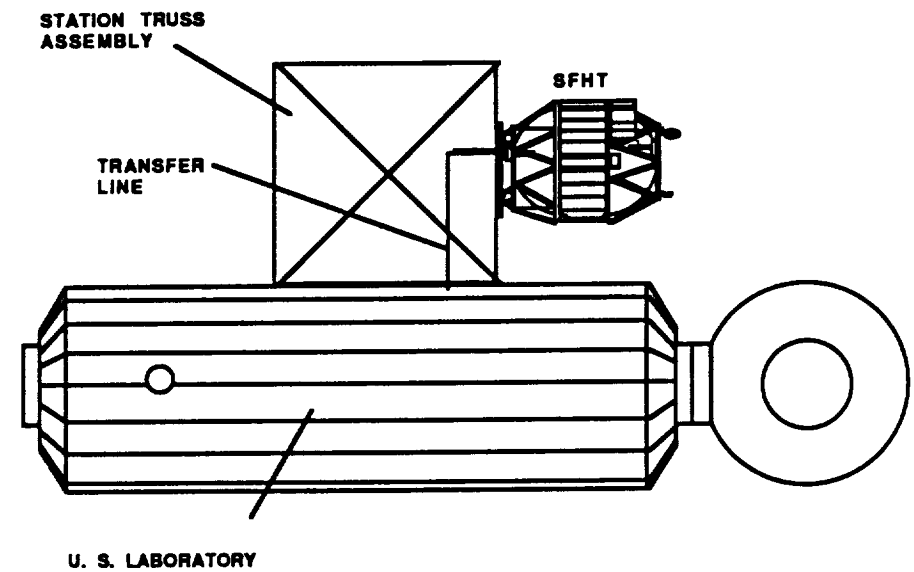


Figure 3.13 SFHT Servicing Operations for U.S. Laboratory Experiments

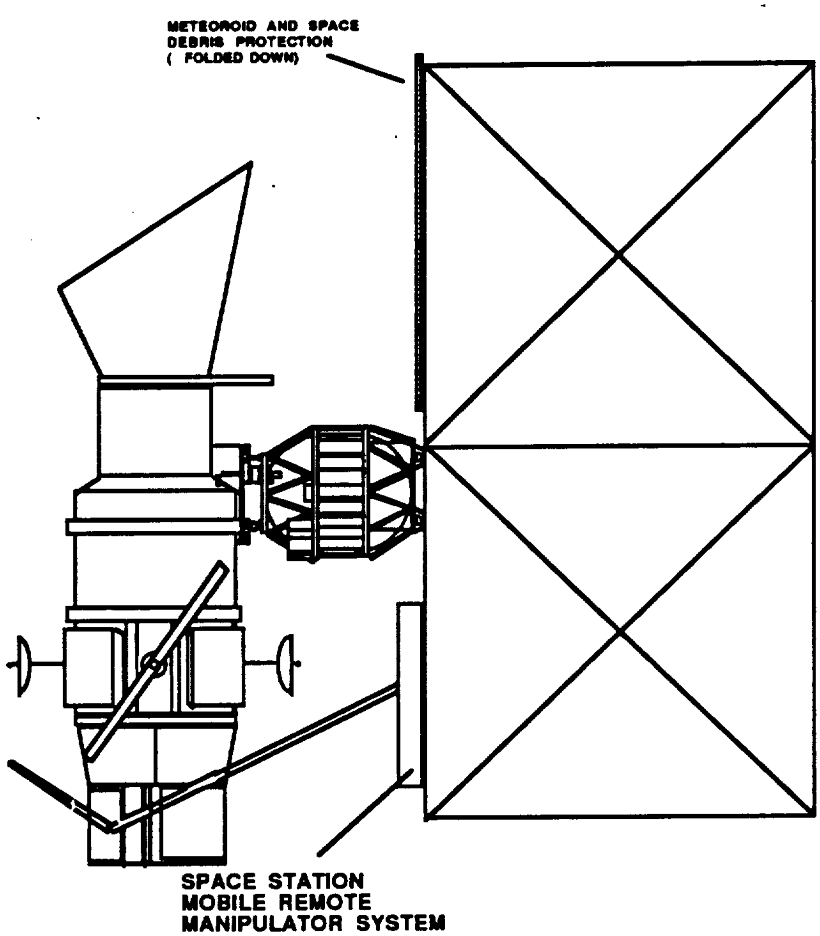


Figure 3.14 SFHT Resupply Operations at Space Station

equipped with a structural docking interface such as the FSS latches. A television camera and light system would be required to perform the docking procedure. Once docking is complete, the active half of the automated coupler mating mechanism would mate the fluid and electrical couplers. Two electrical connectors and two fluid couplers would satisfy mission success requirements. Power and command and data handling would be provided to the user spacecraft from the OMV via the SFHT, with the resupply process being monitored and controlled if necessary from the ground. Upon

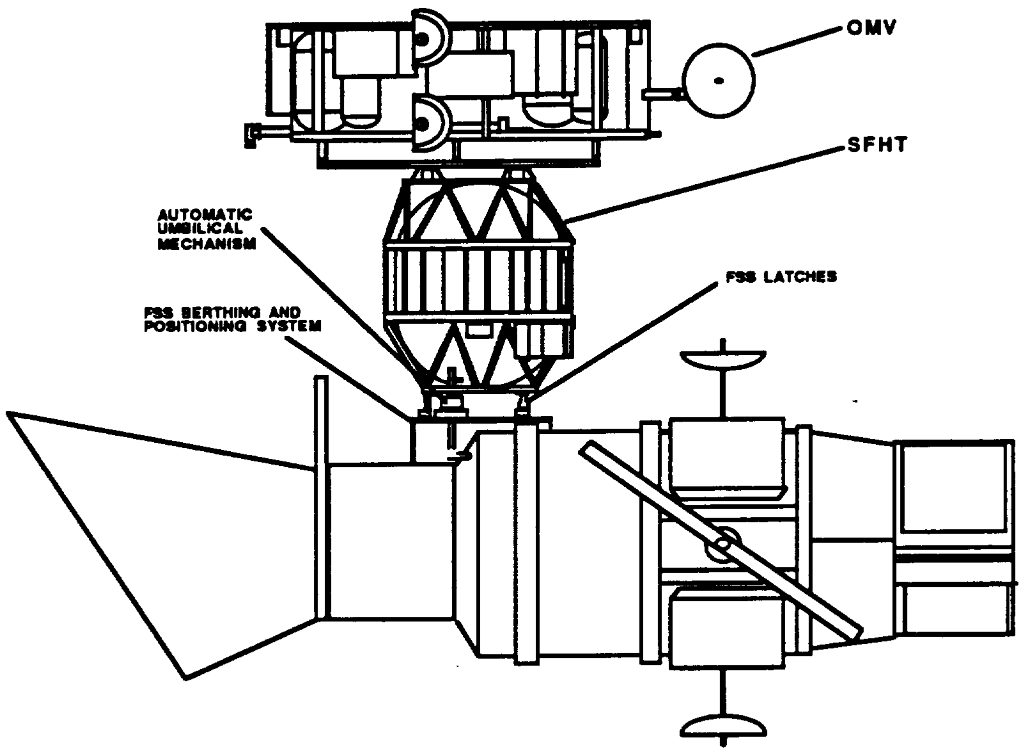


Figure 3.15 SFHT/SIRTF In-Situ Automatic Resupply Interfaces

completion of the replenishment operations, the SFHT would be detached from the user spacecraft and returned either to the Space Station or to the STS.

3.1.3 Fluid Transfer Techniques

3.1.3.1 Transfer Techniques - An analysis was conducted to estimate the total SFHe mass venting losses occurring during the transfer process. Various heating effects throughout the transfer system were considered in calculating these vent losses. In the supply tank, both the parasitic heat leak and the thermomechanical effect were used to calculate the vent loss. The transfer line heat leak and the thermomechanical pump temperature rise were used to determine the thermal condition of the transferred SFHe entering the receiver tank. Vent losses in the receiver tank included the amount of helium vaporized to cool the transferred helium to the receiver tank temperature, and the parasitic heat leak. The total vent loss was the sum of the supply and receiver tank vent mass. Assumptions made in this analysis are as follows:

1 - Line Diameter = 1.27 and 1.91 cm
2 - Line Length = 4.6 m
3 - Storage Tank Volume = 6000 liters
4 - Storage and Receiver Tank Parasitic Heat Leaks = 0.2 watts

5 - Total Transfer Line Heat Leak Including Two Disconnects, a Valve, and the Transfer Line = 4.5 watts
6 - Fluid Transfer Rates = 500 and 1000 l/hr
7 - Receiver Tank Temperature = 1.5 K

The calculated SFHe mass and volume lost during the transfer are plotted in Figure 3.16 as a function of storage tank temperature for flow rates of 500 and 1000 liters/hour, respectively. Each plot presents data for transfer line diameters of 1.27 and 1.91 cm. For the low flow rate of 500 liters/hour, the vent losses for the two line diameters differ by less than 3 kg or 20 liters. At the higher flow rate shown, the vent losses differed by approximately 10 kg or 69 liters. Neither of these losses appear to be a major factor in sizing the storage tank volume. These data do indicate a slight advantage in employing the larger transfer line diameter.

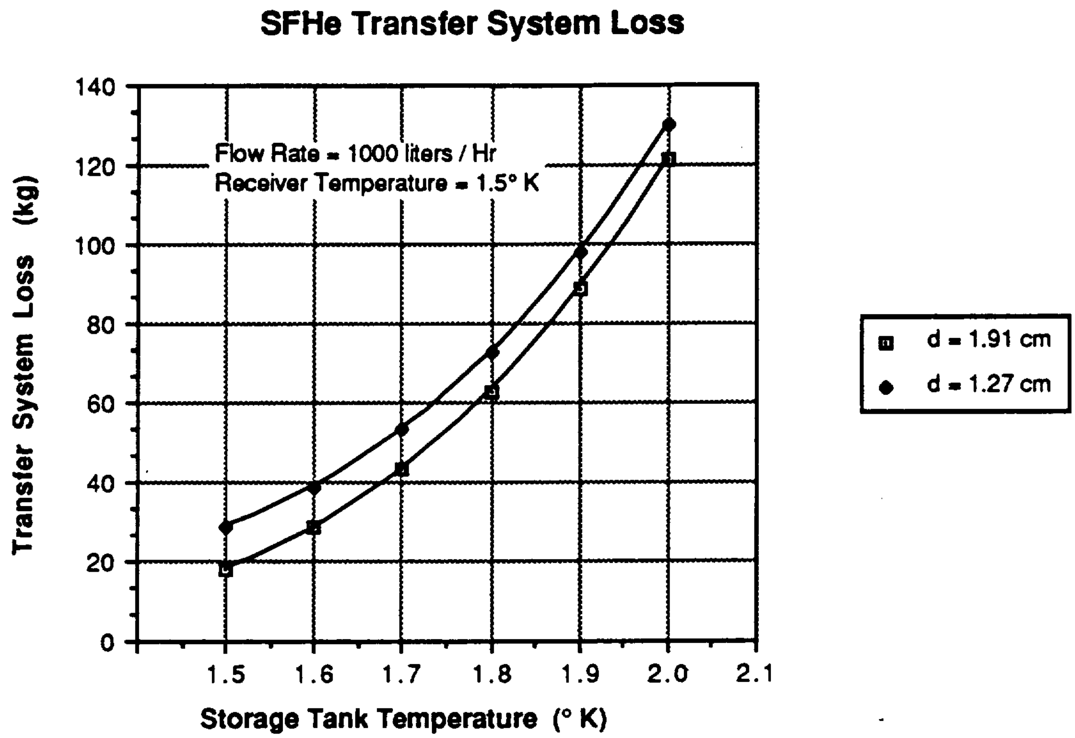
3.1.3.2 System Cooldown - A re-evaluation of the cooldown process was made for a 0.75 inch diameter transfer line. The transfer line length was assumed to be 15 feet. The method for estimating the cooldown requirement was an empirical technique developed by Arthur D. Little, Inc. (Reference 3.15). The transfer line configurations consists of the following components: emergency disconnect, shutoff valve, vacuum jacketed transfer line, and the helium disconnect. All of these components are external to the helium tanker vacuum jacket and are assumed to be initially at ambient temperature (300K). The mass of each component and its steady state heat leak used in this analysis is presented below. It was assumed that the superfluid helium entered the transfer line at a temperature of 1.8 K. The cooldown process was completed when the system was cooled from the initial temperature of 300 K to 2.0 K. The results of the analysis indicated that the time required to satisfy the above requirements was 1.1 hours. The amount of superfluid helium to do the cooldown process was calculated to be 2.47 kg or 17.04 liters.

Component	Mass kg (lbm)	Heat Leak Watts
Emergency Disconnect	1.36 (3.0)	0.5
Shutoff Valve	2.27 (5.0)	0.5
Transfer Line (Flexible)	3.18 (7.0)	2.3*
Helium Disconnect	13.61 (30.0)	1.2
Total	20.42 (45.0)	4.5

*Assumes 0.5 watt/m line length

3.1.3.3 Receiver Dewar Fill - The SFHT must be designed to provide helium to a variety of user systems requiring resupply in space. Consideration of the thermodynamics in the receiver tank during transfer may be important in defining SFHT requirements, and may provide recommendations for design of future systems that will require resupply. In most resupply missions, the receiving Dewar will be cold, and will not be totally depleted of fluid. It is inevitable that instances will occur where the fluid is totally depleted, and the system will have warmed to the ambient temperature. It may also be necessary to supply systems for the first time in space. Therefore, chilldown of the receiving vessel will be a requirement before liquid can be transferred.

One approach for tank chilldown is to evacuate the tank to space, then transfer a small quantity of liquid and hold while heat transfers form the tank to the fluid. Repetition of this process a number of times will cool the tank enough for transfer to begin. This method is complicated by diminished heat transfer processes in low-g. Liquid injected into a warm tank will tend to splatter off the tank wall, and the amount of vaporization that occurs in each contact is very small. Also, the heat sink capacity due to vaporization is only a small fraction of the total available, and much more heat can be absorbed by the vapor. Analysis of the cooldown process by injection of liquid is difficult



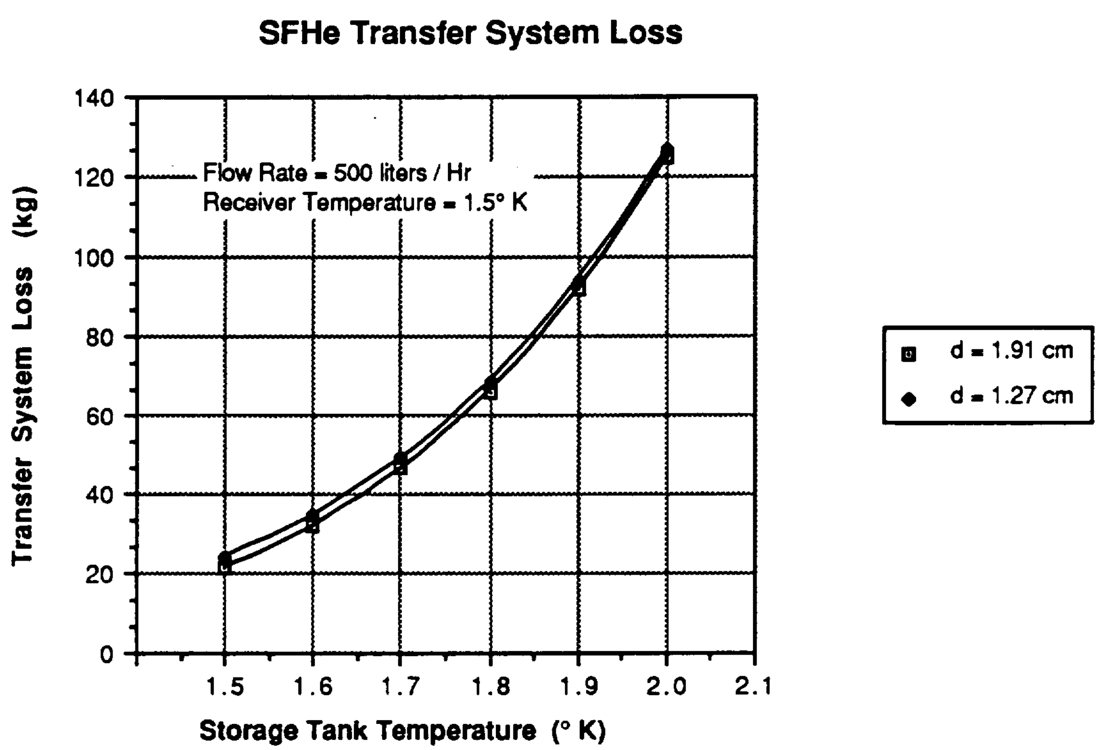


Figure 3.16 SFHe Transfer System Losses

because the low-g mechanics are not adequately understood, but this approach is not likely to be very effective in any event. The use of a cooldown heat exchanger on the tank wall (and probably on the vapor cooled shields) will be more effective, and also amenable to analysis. An adequate heat exchanger would assure full utilization of the heat sink capacity of the cooling fluid, and would minimize cooldown time. This type analysis has been done for SIRTF but should be done for all other users so that total fluid allocation can be determined.

If liquid is transferred into an initially empty tank, part of the first liquid transferred will vaporize, establishing a thermodynamic balance between the temperature of the liquid and the tank pressure. When the pressure reaches the vapor pressure of the entering liquid, vaporization will cease. From this point, the decreasing gas volume requires compression of the gas (with pressure rise) and/or condensation of vapor. The same is true for a tank that is initially partly filled. Once the maximum allowable pressure is reached, further transfer is totally dependent on condensation of the ullage. The heat of condensation must be absorbed into the liquid. For normal cryogens, transfer rate is dependent on heat transfer mechanics within the liquid and the interfacial surface area that tends to decrease as fill progresses. For superfluid helium, however, the rate of transfer is effectively unlimited because of the extremely high rate of heat transfer within the liquid.

Transfer of superfluid helium is therefore less complex than transfer of normal fluids. It is necessary in all cases to provide for the heat sink capacity for the condensation of the vapor, which is normally achieved by subcooling of the entering liquid relative to the final required receiver tank condition. If superfluid helium is transferred using the thermomechanical pump, the energy added in the pump will increase the liquid transfer temperature above that in the supply tank, as will heat leak encountered in the transfer line. Depending on supply tank storage temperature and required final delivered conditions, it will probably be necessary to cool the receiver tank during transfer by operation of a thermodynamic type vent, implemented using the porous plug phase separator.

3.1.4 Fluid Subsystem Design

The SFHT mission will vary as user vehicle requirements vary, and cannot be programmed far in advance. Ability to service a variety of user vehicles in any sequence is a desired capability. Basic to this goal is the ability of the SFHT to maintain superfluid helium on orbit for a long period with minimum boiloff losses. Another design goal is to minimize ground operations, particularly after installation in the launch vehicle. This is of particular importance when the SFHT is launched along with other payloads that will vary from flight to flight. These objectives have been addressed, along with considerations of weight, cost, and complexity, in our trade studies and analyses of the fluid system design.

3.1.4.1 Ground Servicing Concepts - The requirement to supply helium in its superfluid state to user systems does not necessarily define the state of the fluid required at launch. If normal liquid helium is launched, it can be converted on-orbit into superfluid by a venting process. Although normal fluid would be simplest in terms of ground operations, it is not acceptable because of the very large fraction that must be expended in this conversion process. It is therefore deemed a requirement that the liquid be in the superfluid state. It is also necessary that the temperature be sufficiently below the lambda point to provide sufficient heat absorption capacity to prevent normalization due to heating before the on-orbit venting system gains control. Tank pressure at launch remains an option. The tank can be less than 100% filled, in which case the pressure will be the vapor pressure corresponding to the liquid temperature. The tank can also be filled 100% and pressurized.

Helium will be received at the launch site as normal fluid at near ambient pressure, and must be converted either prior to, during, or after loading into the SFHT. It seems clear that transfer of the bulk of the liquid at superfluid temperature is an unnecessary complication as this would require maintaining the SFHT Dewar at a vacuum. Two methods were considered for conversion of the fluid after transferring at about 4.22 K.

In the first, the tank is filled to near the full condition, and then a vacuum pump connected to the tank ullage operates to reduce the pressure to about 12 Torr or below (corresponding to 1.8 K). This initial operation will boil away at least 38% of the initial fill. The process is repeated by again topping the tank with normal helium and pumping back to the desired pressure. A smaller fraction is boiled away because of the lower starting temperature. The desired fill level (to 95% full or more) can be achieved by repeating this process a number of times, as illustrated in Table 3.2. If a very small ullage is desired, a different method for topping is desirable. One approach is to generate superfluid helium externally, in small quantities, and top the tank by transferring superfluid. Transfer could be achieved using gravity feed, a centrifugal pump, or a thermomechanical pump. This approach, however, requires transferring superfluid through a significant length of transfer line, and through at least one disconnect. Because the quantity to be transferred is small, and the flow rate may also be low, the effect of heat leak through these components is magnified, and this method of topping presents a major challenge to the designer of the transfer equipment to achieve the required low heat leak.

Table 3.2 Conversation to Superfluid by Pumpdown

FILL WITH NORMAL HELIUM - PUMP TANK TO COOL

MULTIPLE TOPPINGS REQUIRED

EXAMPLE 6000 L TANK - PARASITIC HEAT LEAK NEGLECTED		
OPERATION	QTY NORMAL HE ADDED	QTY REMAINING WHEN 1.8K REACHED
INITIAL FILL TO 97%	1609 LBM	1001 LBM
TOP TO 97%	746	1476
TOP TO 97%	336	1692
TOP TO 97%	150	1787
TOP TO 97%	67	1831 (95.2%)

The second approach provides an isolated cooling system to convert all of the liquid, after initial fill as normal fluid, as illustrated in the schematic diagram, Figure 3.17. Two-phase helium flows through a heat exchanger inside the tank, and the vapor exiting this heat exchanger proceeds through the three vapor cooled shields. The temperature of this coolant is maintained sufficiently below the temperature of the bulk liquid by maintaining the pressure at the corresponding value. The pressure is regulated by control of the restriction at the inlet, the size of the vacuum pump, and flow losses in the piping as determined by its diameters, length, and heat addition. This concept permits the tank to be filled to a near full condition, and then cooled without any loss of fluid. Topping can be accomplished with normal helium once the pressure goes below ambient (due to cooling) without venting the tank. The final load condition can be saturated superfluid with any desired ullage volume, or the tank can be totally filled and pressurized. The latter condition is easier to achieve. The tank can be pressurized just before the temperature reaches the lambda point (which could be accomplished with normal helium or with vapor) to near one atmosphere and locked up. Because of the negative coefficient of thermal expansion the tank pressure will increase as the fluid is further cooled. Similarly, the pressure will decrease during lockup without cooling as the temperature increases. Loading the tank to leave a desired ullage volume requires an accurate method for determining the liquid level, and possibly a means for offloading to adjust the level.

The independent cooling system offers other advantages. No flight valves need be operated once the final topping is accomplished, and the tank contents are never disturbed. The coolant flow rate can be increased above the required rate to further cool the fluid, and to overcool the vapor cooled shields and multilayer insulation. Overcooling provides added heat sink capability to increase the hold time possible when the system must be locked up and isolated from the ground servicing facility. In case of a long launch delay with the system locked up, the servicing facility can be reconnected in place and the fluid can be restored to the launch ready condition without disturbing the loaded fluid. The servicing facility consists basically of a relatively small (~750 L) Dewar of normal helium and a vacuum pump. We have selected this concept as our baseline. We also recommend pressurizing the SFHT Dewar to about 1.5 atmospheres at launch, primarily to simplify ground operations, but this is an option that is independent of the cooling approach.

In operation of the isolated cooling system, the flowrate and pressure in the heat exchanger are progressively decreased as the tank is cooled down. This must be accomplished by reducing the size of the flow restrictor at the inlet to the tank heat exchanger. The preferred approach is to use a stepper-motor-driven throttle valve, but this function could be accomplished by use of several fixed restrictors and selector valves. As the helium approaches the final temperature, the flow rate decreases to as low as 0.3 L/hour. At such a low flow rate, the heat leak in the normal helium supply line would vaporize most of the liquid. It is therefore necessary to increase the flow

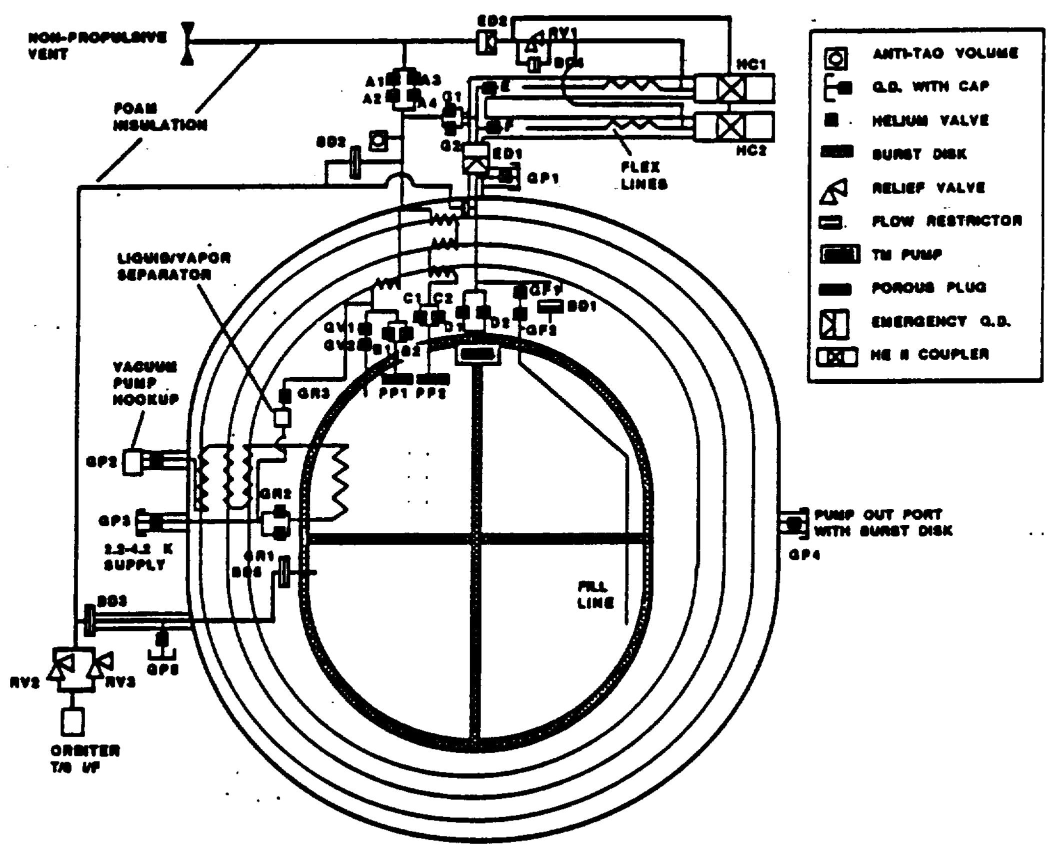


Figure 3.17 Schematic of Baseline Superfluid Helium Tanker

sufficiently to supply liquid to the heat exchanger. This is facilitated by use of a liquid-vapor separator ("keep full") near the restrictor. Vapor from the keepfull is vented through a heat exchanger on the first vapor cooled shield to an ambient vent. By keeping the inner shield colder than normal, a portion of this excess helium benefits the cooldown process. This process has been modeled and results indicate that cooldown to 1.8 K can be achieved in three weeks or less, using the preliminary assumptions of a 250 cfm vacuum pump and 1/2 in. diameter heat exchanger tubing.

A ground hold requirement is the ability for the SFHT to be disconnected from all external support during lockup periods that include transportation to the assembly area and normal and extended launch delays. The helium must remain below the lambda point, and desirably somewhat lower to account for anomalies. In our baseline thermal protection and management system design, the on-orbit heat leak with the vent system operating is approximately 0.18 W. The steady state heat leak without venting is more than 30 times as great, or about 5.5 W. However, the time constant for this system is many days, and transient analyses performed using the CSAM computer program show the following results, starting at 1.6 K.

Overcooling Relative to Space Vent	Days to Reach Indicated Launch Temperature 1.9 K	2.0 K	2.1 K
none	6	7.5	9
125% of flow rate	8.5	10.25	12
150% of flow rate	9.5	11	13
175% of flow rate	11	12.5	14.5
double nominal flow rate	11.5	13	15

These results indicate a more than adequate hold time for the proposed configuration. An approach considered to assure adequate lockup capability is to incorporate a small guard tank inside the insulation, either integral with or thermally connected to the inner vapor cooled shield. This tank would vent at ambient temperature, and would hold the inner VCS temperature to below 5 K, resulting in an almost negligible heat leak to the inner vessel. This option is attractive but does not appear to be required.

3.1.4.2 <u>Fluid Storage and Maintenance</u> - Following proven principles for design of cryogenic storage systems, we have established a baseline design for thermal protection and management. Our baseline is represented in Figure 3.17. Three vapor cooled shields intercept heat leak through the multilayer insulation. A total of 2.6 in (approximately 73 layers) of insulation is assembled onto each of the three shields in the approximate ratio of 11, 25, and 37 layers from the inner to outer shields. No MLI is installed between the tank and the first shield. Rather, care is taken to insure that the emissivity of the tank and shield surfaces is kept low (~ 0.035), by application of reflective tape. This arrangement reduces the net heat leak by about 15% as opposed to installing the same total number of layers in all four spaces because it increases the thickness of MLI in the outer (warmer) regions where it is more effective (relative to radiation between two surfaces).

In a low-g environment, it is difficult and probably impractical to locate a vent so that vapor only can be withdrawn from a tank. Techniques are well established, however, for acquiring liquid by capillary devices using surface tension forces. The thermodynamic vent concept provides for pressure control of a cryogenic storage vessel by admitting liquid to a vent system. The system proposed for normal cryogens draws liquid from the capillary acquisition device. The liquid flow through a pressure reduction device into a tank heat exchanger, in the same manner discussed above for our helium conditioning system. After pressure reduction, part of the fluid vaporizes, cooling the remainder to the saturation temperature corresponding to the pressure int he heat exchanger. This liquid vaporizes, withdrawing liquid from the tank and thereby negating the effect of heat leak. From the tank heat exchanger, the cold vapor flows through the heat exchangers on the vapor cooled shields, intercepting a large part of the inflowing heat, and to the vacuum of space. The vapor cooled shields are thermally strapped to tie-points on the tank supports, piping, and wires, to similarly intercept heat leaking through these components.

The properties of superfluid helium permit a simplification of the thermodynamic vent system. A porous plug, designed to permit a very small flow of normal component helium, is installed in the system so as to be in series with the liquid and the vent leading from the tank. Flow of the normal component fluid results in vaporization at the down stream side where pressure is reduced. The vaporization of part of the liquid results in cooling the remainder to below the lambda point. Because of the lack of viscosity of the superfluid component, it flows back through the plug to the extent of equilibrating the concentration of both sides. The result is an effective replacement for both the tank heat exchanger and the pressure reduction device. This concept, called the porous plug phase separator, has been proven in the laboratory and in space storage of superfluid helium (IRAS & IRT).

Because our design includes the tank heat exchanger and pressure reducer, the use of a conventional TVS design is also an option. Disadvantages of the porous plug phase separator include the need for relatively accurate knowledge of heat load in order to size the device, the possibility for flooding, and lack of control capability. Advantages of the conventional system include the ability for the control system to adjust for changes in load conditions, including shut-off. Simplicity of the plug system and its proven flight record weigh in its favor and this concept is recommended as our baseline.

The vent system has been analyzed using our TVS optimization computer program. In this program, a steady state heat balance is performed repeatedly, varying the distribution of MLI and length of the supports, pipes, and wires between cooling points, until an optimum configuration is found. Total heat leak for the system is 0.175 watts under steady space operating conditions (but with a 300 K vacuum jacket temperature). Steady state heat leak for the same conditions without venting (lockup) is 5.5 watts. This program has also been used to evaluate the sensitivities of results to various design parameters. Figure 3.18 shows the effect of MLI thickness, number of vapor cooled shields, and number of spaces (from the inside) without MLI. Figure 3.19 shows the sensitivity of system performance to external (vacuum jacket) temperature. These results point out that if required, overall performance of both space boiloff and pad hold time while locked up can be improved by increasing the MLI thickness and/or adding a vapor cooled shield. Care must be taken, however, in increasing the thickness of individual MLI blankets, since there is a tendency for degradation of performance as thickness increases due to compaction, bunching, etc. It may be more practical to add both a shield and more MLI if better performance is required.

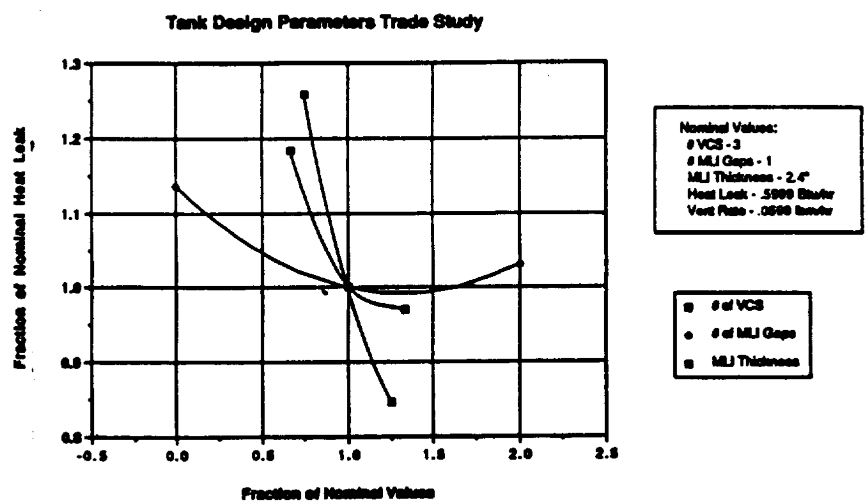


Figure 3-18 Dewar Thermal Parametric Analysis Results

3.1.4.3 Fluid Acquisition Design - The preferred design was described and shown (Figure 4.18) in the Interim Progress Report of February 1988. It uses four separate channels (or galleries) joined at the mid-plane of the tank by a single, circumferential channel. The channel arrangement provides intimate contact with the bulk liquid under any of the probable acceleration vectors. Each channel has a cross-sectional flow area 3.0 inch x 0.75 inch, and incorporates a single layer of 325 x 2300 mesh, double-twilled screen on the 3.0-inch wide wall nearest the tank wall.

The channel dimensions were selected assuming that only one channel is in contact with the bulk liquid during draining at 1,000 L/h under an adverse g-condition of 10-4go. The storage temperature used in the selection process was the lambda point. Based on recent in-house IRAD

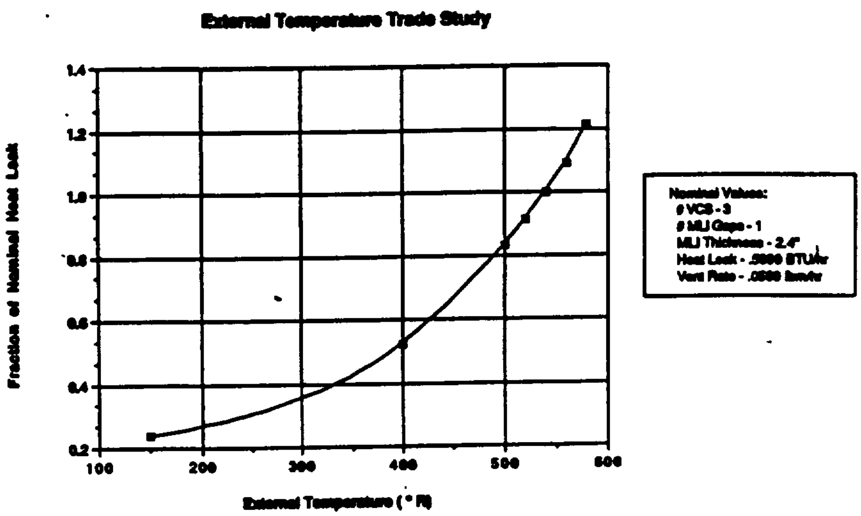


Figure 3.19 Effect of External Temperature on Dewar Heat Leak

tests, a design factor of 2 was used on the bubble point, i.e., the total pressure difference the screen can stabilize to prevent vapor ingestion is 0.00580 psi. The effect of the acceleration magnitude on the screen flow area is presented in Table 3.3. As seen, the screen surface area required by the bulk liquid to enter the single channel and assure single-phase flow increases with the magnitude of the acceleration vector. The conventional Armour and Cannon approach to screen entrance losses was used to determine this term in the equation, and appears to be conservative based on the recent data of Van Sciver (Reference 3.13). The requirement is considered to be minimal. As a result, there will be little or no residuals except for the channels themselves.

3.1.4.4 Emergency Venting - Loss of vacuum can drastically increase heat leak to the SFHT helium vessel, which would result in catastrophic failure if adequate emergency vent capability is not provided. Two modes for loss of vacuum are considered. The first is internal leakage of helium vapor into the vacuum annulus. Only a near microscopic helium leak will change the insulation heat transfer mode to gas conduction, with several orders of magnitude increase in heat leak. Internal helium leakage can occur at any time, and therefore must be considered both in space and under one-g conditions. Leakage of atmospheric air due to damage to the vacuum jacket (the second mode) could cause even greater heating, depending on the size of the air leak, by condensing air on the cold tank.

If anomolous heating occurs in space, there is no assurance that gas or low density fluid would be in the vicinity of the vent exit. This introduces another adverse condition, in that the heating must be assumed to create stratification, or worst case volumetric vent requirements. At the same time, if liquid or high density fluid must be vented, this results in the greatest pressure loss for a given volumetric relief rate. The same assumptions must be made, however, for ground conditions if the tank is totally full, or containing only a percent or two ullage. The agitation caused by high heating

Table 3.3 Acceleration Effect on Screen Surface Flow Area (Channel Dimension: 3.0 x 0.75 in)

Adverse Acceleration, g/go		10^{-5}	10^{-4}	10^{-3}	10^{-2}
Hydrostatic	ΔP, psi	0.00001	0.00005	0.00051	0.00507
Frictional	ΔP, psi	0.00014	0.00014	0.00014	0.00014
Dynamic	ΔP, psi	0.00039	0.00039	0.00039	0.00039
Screen Entrance	ΔP, psi	0.00526	0.00522	0.00476	0.00020
Total ΔP*		0.00580	0.00580	0.00580	0.00580
Screen Surface Area, sq. in.		10.0	10.3	11.0	19.7
Screen Length, in.		3.3	3.4	3.7	6.6
*ΔP = B.P./2					

rates, combined with the low density of helium, will result in at least significant slug flow at the beginning of the vent. It is noted that the first response to loss of vacuum is uniform distribution of heat through the superfluid with no increase in pressure (pressure will decrease if the tank is initially pressurized) because of the high heat transport characteristics. Once the lambda point is reached, however, the high heating rate will result in stratification that tends to maximize pressure rise. We know of no logic that suggests that anomolous heating will be uniformly distributed throughout the fluid, minimizing the rate of pressure rise and mass vent rate necessary.

We have performed analyses using worst case models for stratification, and liquid density in the vent line. A maximum tank pressure of 80 psia has been assumed as the design point for maximum vent flow. A vent rate of 2.22 lbm/sec is estimated for the space anomaly case, with heating caused by conduction through helium vapor. A 7/8 inch vent line (to the 2 inch facility vent) will handle this flow. Our approach is to consider this the primary emergency vent criteria, and to determine the size of air leak into the vacuum jacket that can be tolerated. That leak is determined to be equivalent to a 0.74 inch orifice. However, to increase the ability for the emergency vent to handle larger air leaks, we propose to install a thin layer (1/4 to 1/2 inch) of a conventional (non-vacuum) insulation to limit the ability for air to condense. When air is prevented from condensing on the tank, then the heat leak resorts to conduction of air in the MLI blankets, and convection elsewhere, which is no worse than the helium vapor case. A closed cell foam such as used on the Shuttle External Tank would perform this function, but may result in excessive outgassing in a vacuum jacketed system. The tank mounted insulation would also be wrapped with reflective tape to reduce its emissivity. We are investigating materials for this purpose.

Cork would appear to be an attractive candidate insulation material. It is relatively light and has a low thermal conductivity. However, it would likely need to be sealed to prevent condensation of air within the voids. Martin Marietta investigated the use of cork as a cryogenic insulation that would also have good high temperature characteristics in the 1960s. Results from tests performed indicated a tendency for the cork to break up due to differential thermal contraction, and in the form that it was tested, it did not appear to be acceptable. Experiments using ground cork in an epoxy carrier as a trowellable insulation were more favorable. An outgrowth of this investigation is Martin Marietta's Super Light Ablative (SLA-561). This material is cork in a silicone matrix, and it is used on the Shuttle External Tank in a number of places that are exposed to high heating. An experimental material now being developed by Martin Marietta as aircraft thermal insulation is also being investigated. It will have a lower density, but slightly higher thermal conductivity than

SLA-561. These materials are expected to have acceptable characteristics for this application, and should withstand the low temperature without failure. They can be sprayed on, coated with a sealer, sanded to achieve a suitable surface for the reflective tape, and should not have excessive outgassing characteristics.

Our analysis shows that a layer, about 1/4 to 3/8 inch thick, of one of these materials, will limit the maximum heating rate due to an unlimited air leak to that of the internal helium leak. In addition, heating from the internal leak is also reduced, and the vent line can be reduced to a 7/8 inch tube. Redundancy vents will connect into the 2 inch generic vent lines on either side of the Shuttle, providing 100% backup for pressure relief in the event of vacuum failure.

3.1.5 Structural/Mechanical/Thermal Control Subsystem Design

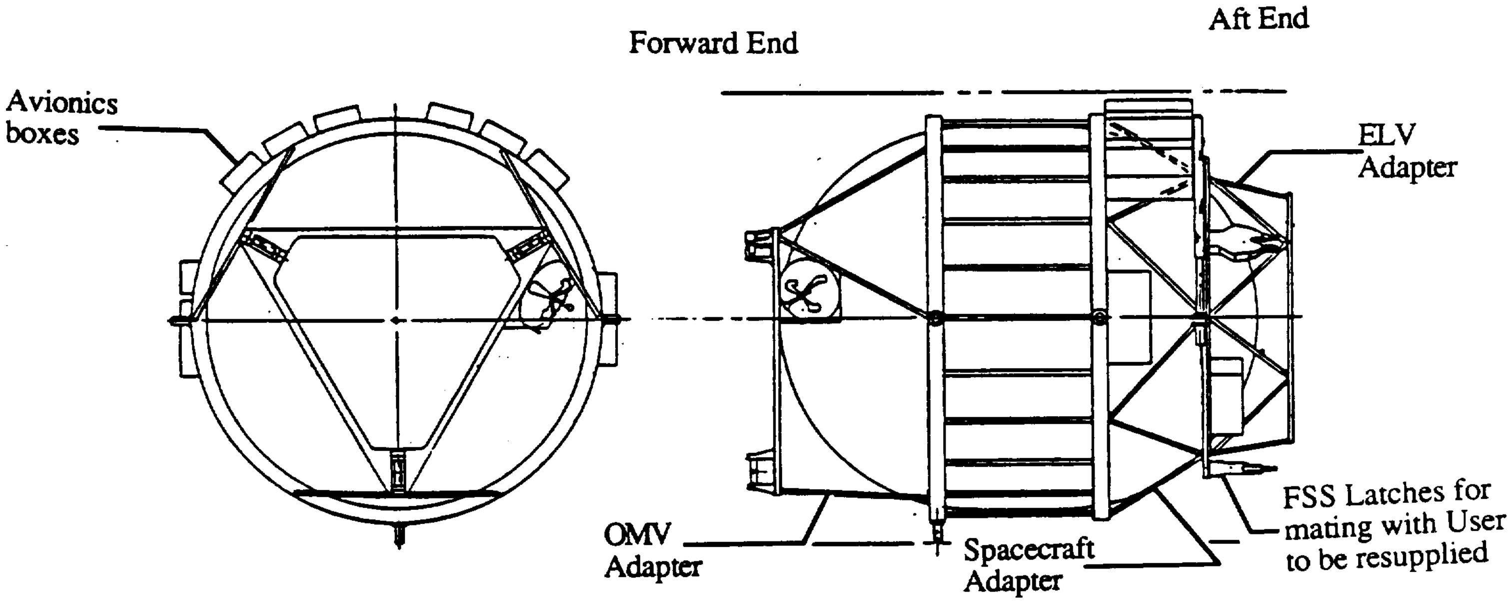
The structural/mechanical and thermal control subsystem design features are discussed in this section. These subsystem designs were configured to permit launch compatibility with both shuttle and ELV launches, and use of the SFHT as a space station depot or with the OMV, as well as servicing from the Shuttle.

3.1.5.1 Structural/Mechanical Subsystem - The SFHT is being designed with the versatility to be launched either on the space shuttle (STS) or on an expendable launch vehicle (ELV), in which case it could be returned on the STS. The STS scenario includes the Dewar vacuum jacket structure, an OMV adapter, a spacecraft adapter for docking with the user on orbit, and a cradle that supports the SFHT in the cargo bay. The ELV scenario includes the Dewar vacuum jacket structure, OMV and spacecraft adapter structures, and an ELV adapter, all of which fits into the 108 inch diameter envelope of the Delta. When the SFHT is launched on an ELV, a cradle will have to be launched simultaneously for SFHT return to Earth. The SFHT structural support concept and the transport cradle are shown in Figure 3.20. All the structure shown is aluminum although approximately 50 pounds could be saved by using graphite/epoxy struts for the adapters instead of aluminum. A statics model has been developed of the Dewar tank and support trusses. This is shown in Figure 3.21.

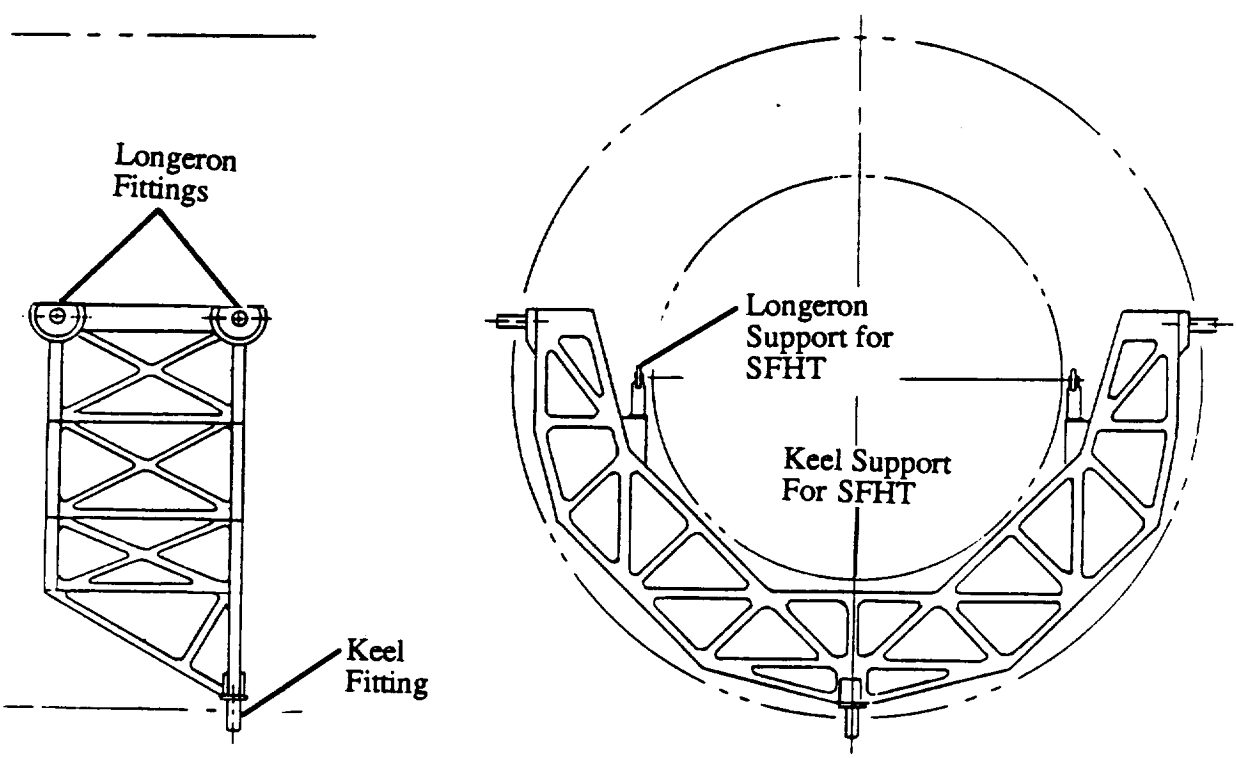
The vacuum jacket structure weighs approximately 1290 pounds, although roughly 150 pounds could be saved by using a more expensive chem-milled skin structure which would require development testing. The two hemispheres (wall thickness $t = 0.125$ inches) are sized for collapse, and to support valving and vapor-cooled shields. A short cylindrical barrel (wall thickness $t = 0.188$ inches) connects the two hemispheres. Longerons are machined into the barrel to transfer axial load from one ring at the aft end of the barrel to a similar ring at the other end. The rings are key to the structure in that they support the inner Dewar, stiffen the vacuum jacket, hold five pins that attach to the cradle, interface with the OMV adapter and the spacecraft adapter, and support an avionics platform.

The Orbital Maneuvering Vehicle (OMV) adapter weighs approximately 283 pounds. It mounts to the forward ring with six struts that separate FSS/OMV latches from the hemisphere. At the forward end the struts attach at 3 places to a machined triangular frame, on which the latches and two RMS grapple fixtures are mounted. Note that the latches make up 67% of the subsystem weight.

On the aft end of the Dewar vacuum jacket is mounted the spacecraft adapter, weighing 328 pounds. It is sized for ELV loads since it connects the vacuum jacket to the ELV adapter. Twelve struts space the aft ring from the vacuum jacket. Six separation fittings and three FSS fittings are attached to this ring. Additional equipment, including tool boxes, are mounted on this truss.



a) SFHT Configuration for ELV Launch (or placement in Transport for STS Launch)



b) SFHT Transport cradle for STS Launch and/or Return

Figure 3.20 SFHT Structural Support Concept

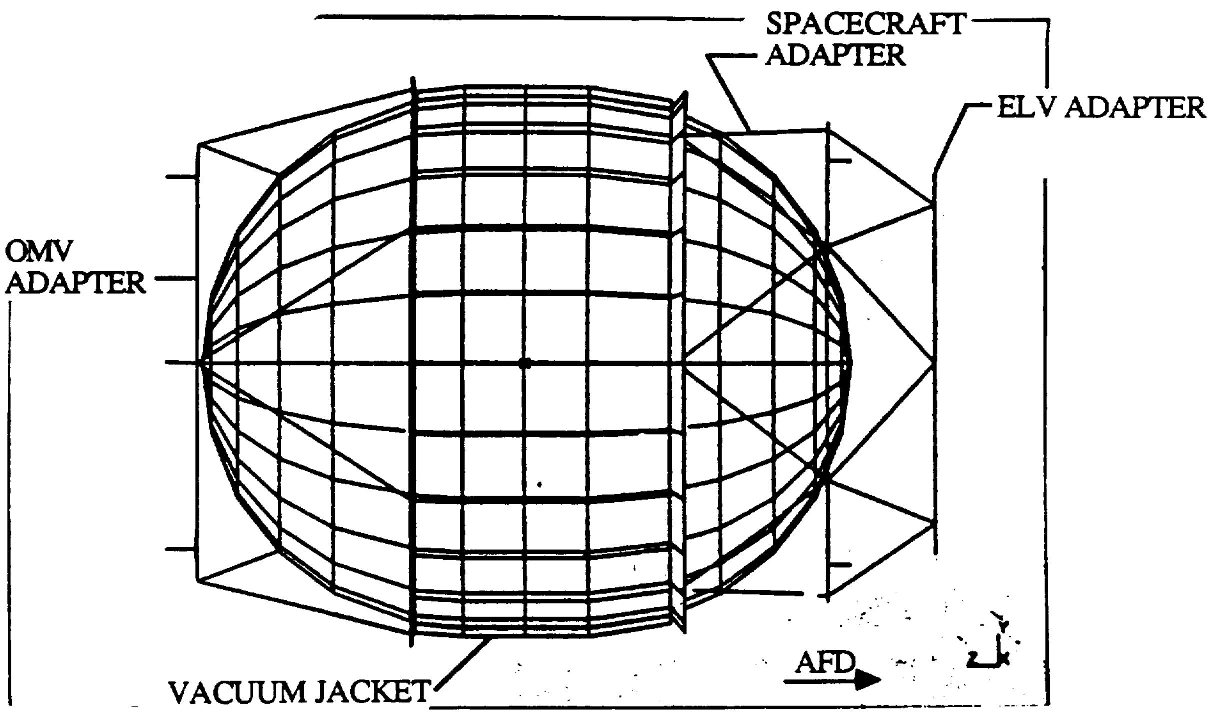


Figure 3.21 Statics Model of SFHT Tank and Support Trusses

The ELV adapter, which stays with the ELV after separation, interfaces at six points to the spacecraft truss. This will be a mechanical, as well as electrical, separation. It weighs 138 pounds and can be built to adapt to any ELV interface diameter and number of discrete attachment points. A Delta adapter is shown in the sketch.

Finally, the transport cradle will be mounted in the Orbiter to support the SFHT at four longeron and one keel latch. Each of these fittings weighs 44 pounds. The transport cradle itself also mounts to the Orbiter with four longeron and one keel fitting. The cradle weighs approximately 1200 pounds based on similar designs we've fabricated and qualified.

The total structural weights for various launch options, using the individual adapter and vacuum jacket weights listed above, are:

> 3239 pounds for ELV launch and STS return,
> 3101 pounds for STS launch and STS return,
> 2039 pounds for ELV launch (single use SFHT).

3.1.5.2 Thermal Control Subsystem - A thermal control design has been selected to be compatible with the Orbiter, OMV, and Space Station. The design allows flexibility in orientation so that mission constraints imposed by other vehicles do not occur. The table below presents the derived thermal control requirements which were used for the thermal control subsystem conceptual design.

Thermal Requirements Summary for SFHT

Environments

Orbiter Payload Bay - 250 nmi to 270 nmi, Attitudes per ICD 2-19001 including 30 minutes facing direct sun, 90 minutes facing deep space

Space Station - 250 nmi, Meteoroid shielded enclosure, avg. internal radiative environment <0 °C (goal)

OMV Operations - 250 nmi to 486 nmi, No attitude constraints imposed on OMV by SFHT

Sun Angle (Beta Range) - Mission dependent, use 0° to 90° for design

Atomic Oxygen Fluence - Mission dependent, use resistant materials and coatings

Equipment Temperature Limits (Flight Allowables)

Avionics Components: -10 °C to 45 °C

Battery: -18 °C to 32 °C

Dewar Exterior: Provide low temperature environment with low risk, passive approach

Heat Loads

Hot Case Design: 201 W orbital avg. (includes 20% margin)

Cold Case Design: 20 W orbital avg.

Thermal Design Criteria

Heater Power Margins - Design for a 50% margin at lowest predicted temperature and 26 V source

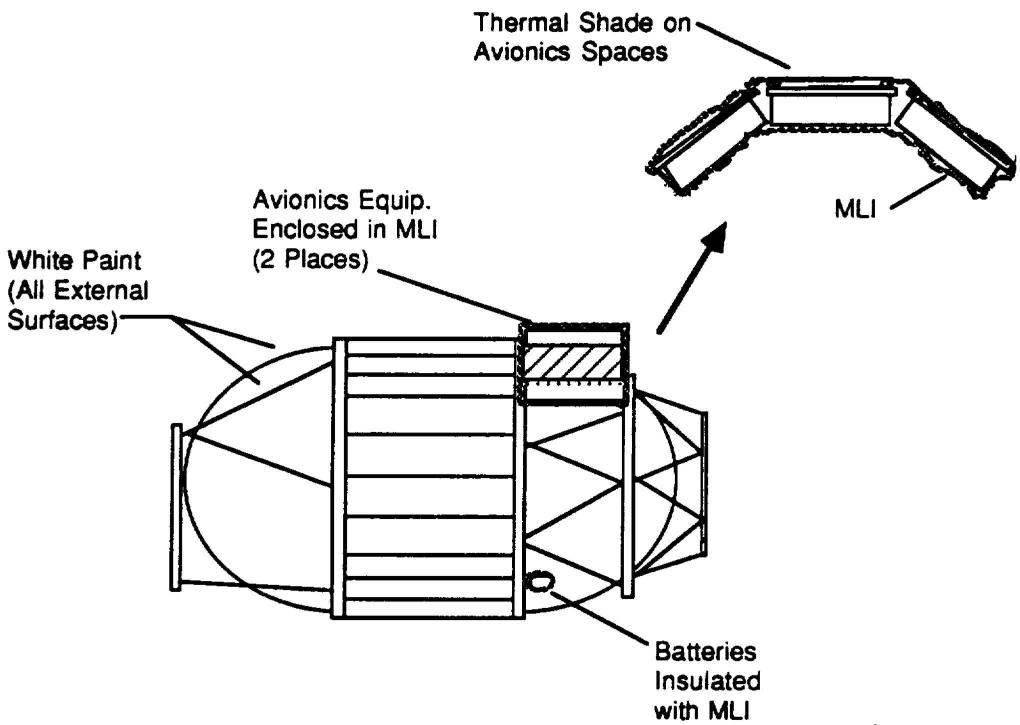
Heater Redundancy - Heater elements will be redundant and each element will have at least two thermostats in series. The primary and secondary circuits will have different temperature set-points. One heater failed "on" will no overheat the vehicle.

Temperature Predictions - Shall be 10°C inside equipment acceptance temperature range. Heaters or active control allows predictions to be equal to acceptance temperatures.

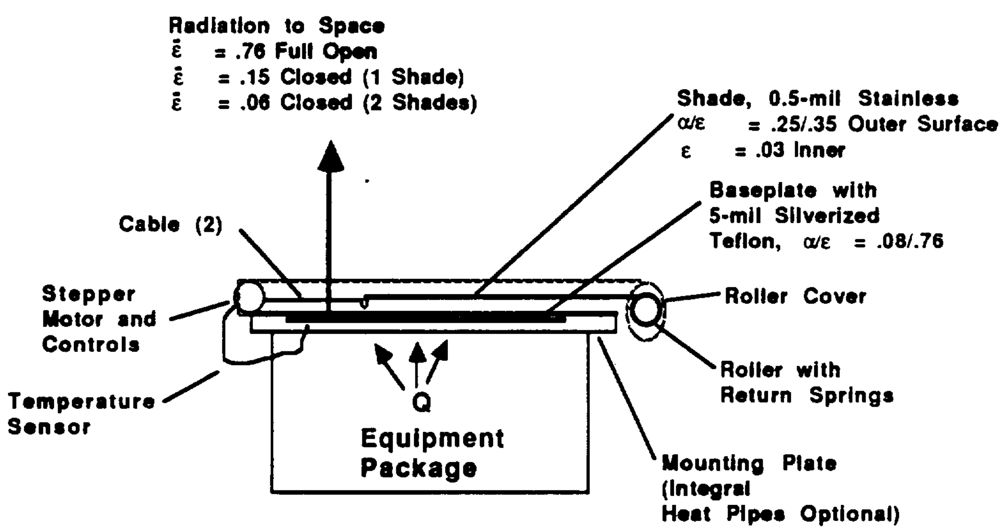
Thermal Control Concept - The key features of our thermal control concept are shown in Figure 3.22. The external surfaces on the Dewar and its supporting structure are painted white to limit their temperature excursions in the orbital environments. The avionics equipment is enclosed in two thermally controlled spaces covered with multilayer insulation. Temperature control in these spaces is provided by a movable shade which varies the equipment baseplate's view to space in response to a temperature sensor. This approach allows the avionics equipment to operate over a wide range of orbital environments. The shade was selected over louvers to allow efficient operation under conditions of direct solar input.

Dewar Exterior Thermal Control - White paint was selected for the external surfaces of the Dewar and its supporting structure. Alternatives include adding additional MLI shields and/or second surface coatings such as optical solar reflectors (OSRs) and silverized teflon. Preliminary analyses of these options indicated that the benefits of these measures (e.g., reduced Dewar surface temperatures) did not justify their added cost and weight impacts.

White paints can provide solar absorptivity-to-emissivity ratios in the range of 0.3 to 0.5 while OSRs and silverized teflon can achieve values below 0.1. For low Earth orbit heat fluxes, this results in average surface temperatures (for the specific case of a nadir-pointed cylinder) ranging from 235 K for white paint to 225 K for the second surface coatings. The savings in helium boiloff for the short duration SFHT missions does not offset the cost and weight associated with OSRs or second surface coatings.



a) Thermal Control Concept



b) Thermal Shade Features

Figure 3.22 Thermal Control Concept and Thermal Shade Features

For longer duration storage conditions (e.g., attached to the space station) the SFHT will be parked in an meteoroid protection enclosure that will provide effective shielding from solar inputs. This situation again negates the need for high performance external Dewar surfaces.

Avionics Thermal Control - The high dissipation electronics will be packaged within two thermal control volumes insulated with MLI. Heaters will maintain temperatures above lower limits and a thermal shade will provide temperature control by varying the view to space of the equipment baseplate. The control volumes are designed to 1) allow full power avionics operation in a hot environment with direct solar input to the heat rejection surface, and 2) to minimize heater power in a cold, deep space environment with no external heat fluxes.

Louvers were compared with the thermal shade approach in an analysis which determined heat rejection areas and heater power. The avionics equipment was assumed to operate over the range of -10°C to 45°C. Both devices were assumed to be totally closed at 0°C and to be full open at 27°C. The equipment baseplate was covered with 5-mil silverized teflon.

Results of the study indicated each volume required radiator areas of 6.8 ft^2 per 100 W for louvers and 4.2 ft^2 for a thermal shade. The heater power to offset the loss through the louvers in the cold case was 19 W for each avionics space compared with 6.3 W for the thermal shade concept. Preliminary weight for both approaches is estimated to be 12 pounds.

The thermal shade has been selected as the preferred approach at this point in the conceptual design, although additional effort is needed to assess cost, reliability and detailed packaging considerations. Two large thermal shades (18 ft^2 and 12.5 ft^2) have been flight-qualified by Martin Marietta on a defense program. Additional development would be required to scale the existing design down to the SFHT requirements.

Louvers are flight-proven devices with a heritage of high reliability and well understood manufacturing processes. The louvered approach could be easily implemented if the additional area (and mass) can be allocated in the detailed design phase.

Our analysis indicates that nominal orbiter bay temperatures will range from -73°C to -4°C when the bay is not directly viewing the sun. This is an acceptable environment for all the external elements of the tanker. The two avionics spaces will be located on the tanker structure adjacent to the orbiter doors to maximize the shade's view to space. Electrical heaters and thermostats will be used to maintain minimum allowable temperatures. Since no safety issues are present in the thermal control subsystem, a two-fault system is not required.

External Plumbing - Temperatures of exposed plumbing (valves, vents, lines, etc.) must be controlled to minimize their heat leak. If these components are maintained at 300 K or lower, their heat leak contribution to the 200 K shield is less than 1%. Encapsulating pipes together under a single thermal surface with multilayer insulation will minimize heat gain to the helium tank. White exterior surfaces will minimize temperature due to solar exposure. As mentioned previously, some lines and components will already be covered by foam insulation or a vacuum jacket and thus will not need further temperature control.

Thermal Components - Standard components which are space qualified are available for this design. The thermal shade, which is somewhat unique, has been flight qualified on another Martin Marietta program. Film heaters of etched nichrome metal laminated between Kapton film will be used. Mechanical thermostats will be used with an arc suppression circuit on each thermostat to assure long life. The insulation blankets on the two avionics volumes will be comprised of double aluminized Mylar film, Dacron net spacers, filter cloth, Kapton facing, and Gortex Ortho cloth. The Mylar will have an acrylic overcoat to protect the aluminization from water vapor damage which can be experienced during earth atmosphere return. The exterior Gortex Ortho cloth was selected because of its optical properties (α/ε = .18/.84) and its toughness. Standard stitching and grounding straps will be used.

The design of the thermal shade is shown in Figure 3.22. The electronic mounting structure is covered with the silverized teflon to maintain a low temperature in a solar environment. The shade is similar to two curtin shades rolled upon each side of the mounting plate. When the plate cools during reduced power modes, a stepper motor pulls the shade closed. The stainless steel shade is highly polished internally which hinders radiation transfer. The shade is pulled further closed with additional reductions in mounting plate temperature. The exterior surface of the curtin is coated with a 1000 angstrom aluminum protected by silicon oxide to limit its temperature in a solar environment. The two rollers are cabled together such that both close equally. The motor control is activated by temperature sensors in the mounting plate.

3.1.6 Avionics Subsystem Design

3.1.6.1 Instrumentation - To properly monitor and maintain the superfluid helium in its desired state, both on the ground and during a refueling operation on orbit, the tanker must provide the capability to accurately monitor the temperature, pressure, and mass of the liquid. To accomplish this the instrumentation baselined for the SHOOT experiment is baselined for the superfluid helium tanker. The particular sensors identified for the SHOOT experiment provide the accuracy necessary to manage the fluid in storage and during a refueling process as well as providing a proven design concept certified with flight experience. A list of instrumentation within the tanker fluid system is provided in Table 3.4; Figure 3.23 indicates sensor position.

Temperature measurements will be obtained with Germanium Resistance Thermometers (GRT) and Platinum Resistance Thermometers (PRT). The GRTs provide excellent accuracy in the temperature range of superfluid helium (1.3K to 2.1K) and will be used to monitor liquid temperature up to 40K. To monitor the temperature of subsystems or subelements above 40K, PRTs will be utilized. Each GRT and PRT will be in a four wire configuration, two wires for excitation and two wires for sensor output. We propose using the Temperature and Pressure Measurement System (TPMS) units developed for the SHOOT experiment to provide the excitation and monitor the sensors. Excitation will be multiplexed to the GRTs and PRTs to prevent excessive heat input to the liquid. Multiple sensors will be provided to ensure system reliability.

Pressure measurements will be performed using a diaphragm-type differential pressure sensor. The diaphragm is of steel construction which allows usage of the pressure sensors in a cryogenic environment. Each pressure sensor will be in a four wire configuration with excitation and sensor monitoring being performed by the TPMS units. Due to the construction of the pressure sensor diaphragms, the excitation will be provided by an AC voltage source. Multiple sensors are provided to ensure system reliability

Liquid mass will be determined by inputting a heat pulse into the helium and monitoring selected GRTs to determine the change in temperature. The rise in temperature is then related to liquid mass through the helium specific heat characteristics. This technique is proven and provides the desired accuracy to know liquid mass; it is being specified by the SHOOT experiment for determining liquid mass. GRT excitation and monitoring will be via the TPMS units as described for the temperature sensors. Only one GRT is required to determine the liquid mass; to ensure system reliability multiple sensors are included.

Determining the mass of the liquid while on the ground will require the use of superconducting wire probes. This technique is restricted to ground usage for loading and storage. In a zero-g environment the superfluid liquid may deposit a film on the wires inhibiting accurate mass

Table 3.4

MEAS. ID	MEASURES	RANGE	SAMPLE RATE	FUNCTION	REMARKS
P1	Tank Press	0-100 Torr	.1/sec	On-Orbit tank pressure	redundant if necessary
P2	Tank Press	0-3 ATM	.1/sec	tank press during gnd/launch ops	redundant if necessary
P3	Phase separator, down stream pressure	0-20 Torr	.1/sec	monitor vent phase separator ops	
P4	VCS exit pressure	0-20 Torr	1/sec	monitor TVS ops	
P5	Ground refrig tank Hx pressure	0-20 Torr	1/sec	used during fill, conditioning & gnd hold	
P6	Inlet to gnd refrig VCS	0-20 Torr	1/sec	used during fill, conditioning & gnd hold	
P7	gnd refrig exhaust press	0-20 Torr	1/sec	used during fill, conditioning & gnd hold	
P8	Gnd refrig line supply pressure	0-3 ATM	1/sec	used during fill, conditioning & gnd hold	
P9	fill/drain line press	0-3 Torr	1/sec	used during fill, conditioning, gnd hold, & xfer	(monitor locked-up volume)(may need dual range for xfer)
P10	fill/drain line press	TBD	TBD	monitor locked-up	if required
P11	press in trapped volume (flex line-to-spacecratf)	TBD	TBD		if required
P12	press in trapped volume (flex line-to-spacecratf)	TBD	TBD		if required
P13	overboard vent pressure	0-200 PSI	1/sec	monitor xfer operations	
P14	overboard vent pressure	0-200 PSI	1/sec	monitor xfer operations	redundant sensor
T1-T4	internal tank temps	0-5K	1/sec	monitor He temp during gnd & flight ops	
T5	gnd req tank Hx exit temp	0-5K	1/sec	monitor loads cooldn & gnd hold operations	
T6	gnd refrig VCS exit temperature	100-300K	1/sec		
T7	VCS exit temperature	100-300K	1/sec	monitor TVS/VCS performance	
T8	VCS exit temperature	200-300K	1/sec	monitor TVS/VCS performance	
T9	treansfer line temp	0-5K/ 0-300K	1/sec	monitor chilldn/ transfer temp	
T10	temp at disconnect	0-5K/ 0-300K	1/sec		
T11	temp at disconnect	0-5K/ 0-300K	1/sec	monitor VCS performance	redundancy as req-tbd
T12	VCS #1 temp	0-100K/tbd	.1/sec		
T13	VCS #2 temp	0-200K/tbd	1/sec	monitor VCS perform	redundancy as req-tbd
T14	VCS #3 temp	100-300K	1/sec	monitor VCS perform	redundancy as req-tbd
T15	FEP inlet temp	0-5K	1/sec	monitor pump pressure	
T16	FEP outlet temp	0-10K	1/sec	monitor pump pressure	
T17	transfer line temperature	0-5/0-300K	1/sec	mont chilldn/xfer temp	redundancy
Q1	quantity of SFHe in tank	0-1000Kg	1/sec	tank gauge	
Q2	quantity of SFHe in tank	0-1000Kg	1/sec	tank gauge	redundancy-if required
V1	FEP heater voltage	0-30VDC	1/sec		
V2	FEP heater voltage	0-30VDC	1/sec		
I1	FEP heater current	0-1.44 Amp	1/sec		
I2	FEP heater current	0-1.44 Amp	1/sec		
F1	transfer vent flow rate	TBD	1/sec	monitor xfer operations	
F2	transfer vent flow rate	TBD	1/sec	monitor xfer operations	redundancy
F3	overboard vent flow rate	TBD	1/sec	monitor vent system operations - backup to mass gauge	venturi flowmeter
F4	overboard vent flow rate	TBD	1/sec	monitor vent system operations - backup to mass gauge	venturi flowmeter

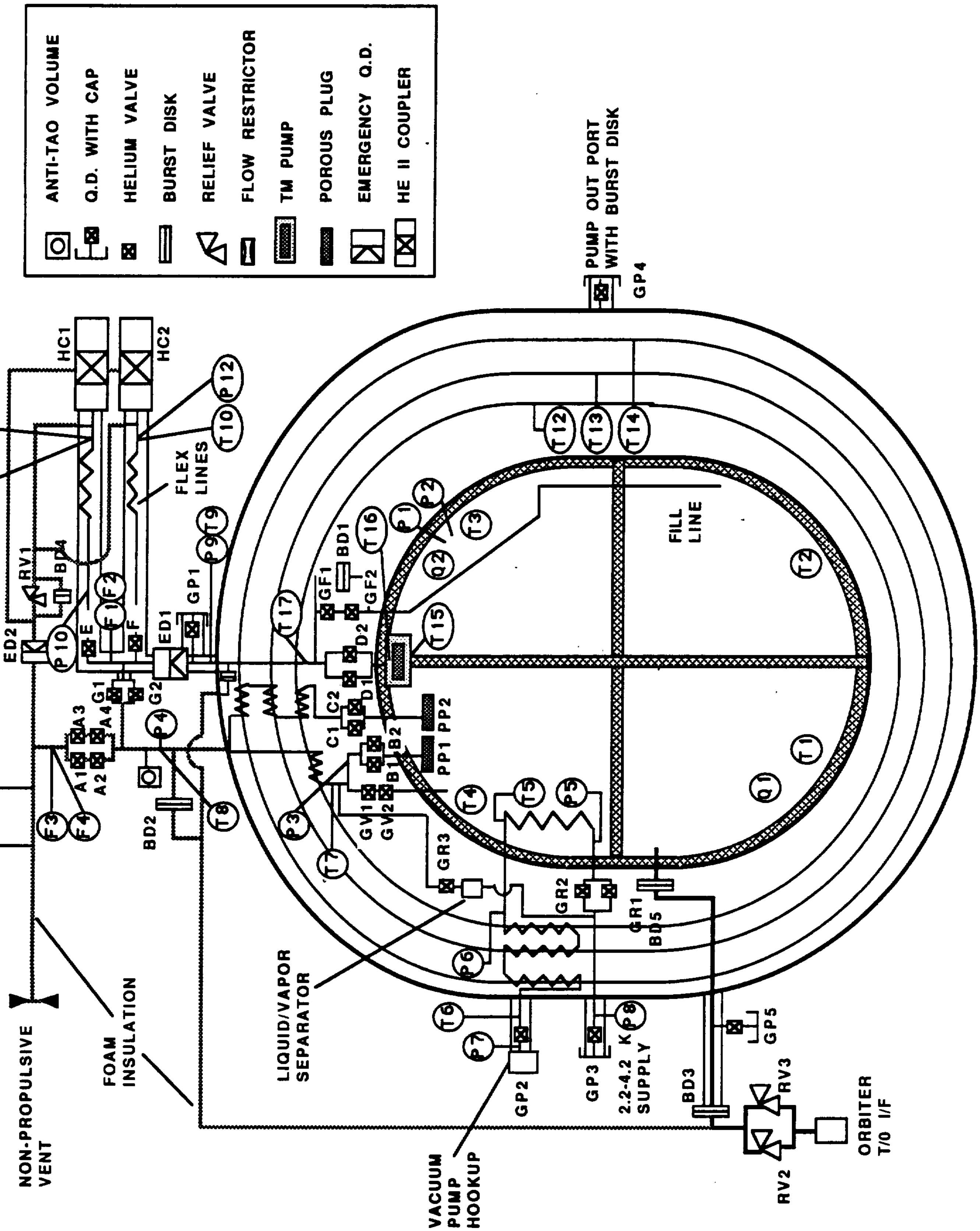

ANTI-TAO VOLUME
Q.D. WITH CAP
HELIUM VALVE
BURST DISK
RELIEF VALVE
FLOW RESTRICTOR
TM PUMP
POROUS PLUG
EMERGENCY Q.D.
HE II COUPLER
PUMP OUT PORT WITH BURST DISK
GP4
HC1
HC2
FLEX LINES
FILL LINE
LIQUID/VAPOR SEPARATOR
NON-PROPULSIVE VENT
FOAM INSULATION
VACUUM PUMP HOOKUP
2.2-4.2 K SUPPLY
ORBITER T/0 I/F
RV1
RV2
RV3
BD1
BD2
BD3
BD4
BD5
GP1
GP2
GP3
GP5
ED1
ED2
PP1
PP2

Figure 3.23

readings. A constant current excitation will be supplied by the TPMS units. The mass of the liquid will be determined by monitoring the voltage drop across the superconducting wires. The voltage is then correlated to the mass of liquid in the tanker.

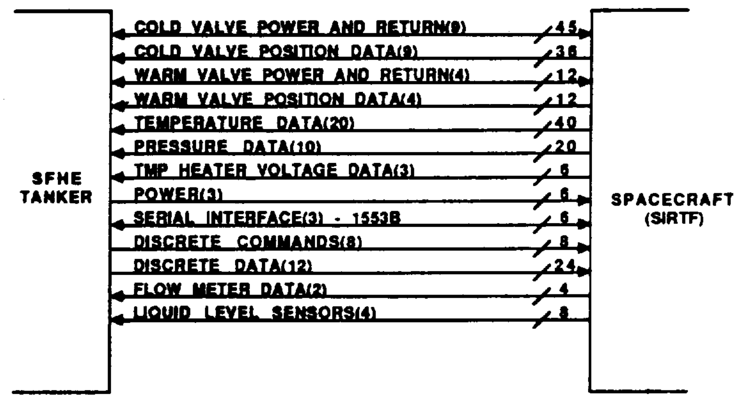
Flow measurements will be provided by redundant venturi flow meters. Each flow meter has two differential pressure sensors for redundancy. The rate of liquid flow through the meter is correlated to the data from the pressure sensors. Excitation and monitoring of the flow meter pressure sensors will be via the TPMS units as described for the pressure sensors.

3.1.6.2 Tanker Avionics Subsystems - The SFHT avionics subsystem is designed to provide the capability to command, control, and monitor the SFHT during a superfluid helium resupply mission. The design requirements as referenced from the System Requirements Document are as follows:

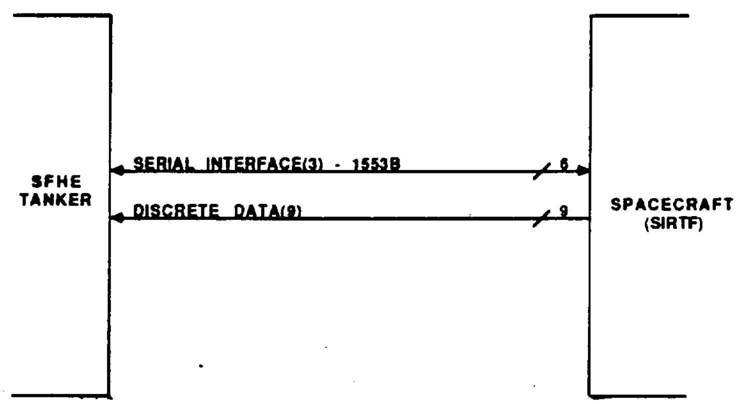
a) Provide electrical interfaces to the receiving satellite and to the Orbiter. These interfaces include power, command, and control and monitoring.
b) Provide power distribution, control, and monitoring for both SFHT and the user satellite
c) Provide valve control and monitoring for both SFHT and the satellite
d) Provide control and monitoring of mechanisms associated with berthing and emergency separation
e) Provide instrumentation as required to operate and monitor SFHT
f) Provide signal conditioning of SFHT and satellite data
g) Provide the man-machine interface for crew control of the resupply operation from the Aft Flight Deck of the Orbiter. The man-machine interface includes provisions for operator inputs, alphanumeric and graphic displays of SFHT and satellite data, and caution and warning data displays and annunciation

The interface to a user satellite will incorporate the capability to monitor and control the satellite in a powered-up or powered-down condition. Figure 3.24 shows interfaces configured for the SIRTF satellite. The interfaces were discussed with Ames Research Center personnel working SIRTF. If SIRTF is in a powered-down condition the interface provides power, commands, and monitoring capability of the SIRTF. Power to the satellite will be 250 watts maximum, switch-controlled by the crew in the AFD. Discrete commands, bilevel monitors, and analog monitors are provided to control and monitor a limited number of satellite subsystems. Commands are actuated by the crew with satellite data displayed on touch-screen displays in the AFD. A serial link (1553B) is available to the satellite. This provides the satellite the capability to transmit system status to the tanker instead of being limited to a few monitoring channels. If SIRTF is in a powered-up condition all communication between the tanker and the satellite occurs through the serial interface. The tanker will transmit commands to the satellite command system, where the satellite will control its own subsystems. Monitoring of satellite data will be collected by the tanker, processed, and displayed on the AFD displays. No power will be provided to the satellite.

Simplifying the interface between the tanker and the satellite can be accomplished by requiring that: 1) the satellite operate off its own power source, and 2) the satellite provide control of its own fluid subelements. Figure 3.24 shows the simplified tanker-to-satellite interface. The serial link (1553) provides a path for commands and data between the tanker and satellite. Commands to the satellite can be uplinked or stored within the tanker CPUs memory. Data is collected by the satellite and transmitted to the tanker for processing and/or downlinked to the ground. In this simplified approach the command and monitoring interface is less complex and wire count is reduced. The tanker CPUs will verify all satellite bound commands to ensure mission success and safety but otherwise remain transparent to the satellite. The discrete data in the interface is required to determine proper mating of the electrical connectors in the tanker-to-satellite interface.



a) Spacecraft Interface with SFHT Providing Power and Control



b) Simplified Spacecraft Interface with SFHT

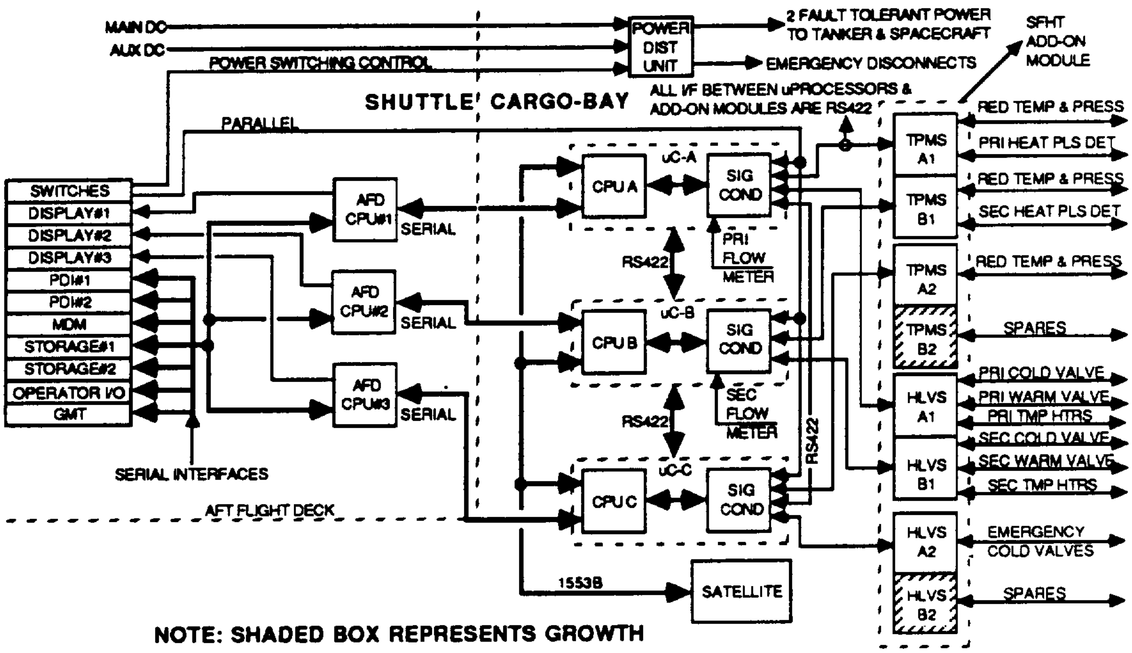
Figure 3.24 SFHT-Spacecraft Avionics Interfaces

The SFHT avionics is divided into two sections, AFD subsystem and Tanker (cargo bay) subsystem. Figure 3.25 shows a block diagram for the SFHT flight system, assuming that we retain much of the redundancy and fault tolerance put into the OSCRS avionics design.

The AFD subsystem provides the man-machine interface for crew monitoring and control of the resupply operation. The subsystem is triple redundant and provides two fault tolerance to commanding and monitoring SFHT and the satellite. The displays are flat panel color displays with touch-screen command capability. The crew will control the resupply process by actuating commands from the touch-screens. Each CPU will process and relay the commands to the tanker subsystem through a dedicated serial interface (RS422). Command actuation will be a two stage process (validate/correct) before relaying the command to the tanker. This will prevent any inadvertent valve operations by the crew.

Monitoring of SFHT and satellite data, and providing the information to the crew, is controlled by the CPUs. The CPUs acquire data from the tanker subsystem through the serial interface, and process the data and control the display of data on the three flat panel displays. Intrafacing will exist between the CPUs for sharing of SFHT and satellite data, and CPU housekeeping data. This provides the capability to warn the crew of a CPU malfunction if one of the CPUs is having difficulty. The crew can then take the necessary action to correct the problem or shut down the

Figure 3.25 SFHT Avionics System Diagram Assuming Maximum Commonality with OSCRS Avionics



problem CPU. The CPUs will provide caution and warning of any tanker or satellite parameters that may be out-of-limits and display the data to the crew.

Orbiter interfaces required by the AFD subsystem are the Payload Data Interleaver (PDI) and the Multiplexer Demultiplexer (MDM). The PDI will be utilized for downlinking data. Two channels are required; a primary channel for real time data, and a secondary channel for stored data. The MDM interface provides an optional interface to the Orbiter General Purpose Computer (GPC). Mass storage is provided in the event of loss of signal to the ground by the Orbiter.

Power to the AFD subsystem will be two fault tolerant. Main Orbiter power for mission success, Aux power for mission safety, and battery backup in the event of Loss-of-Service from the Orbiter. The battery is required to provide the crew the capability to control the actuation of tanker pyrotechnic devices to activate the emergency disconnects to ensure satellite - tanker separation. Table 3.5 gives a list of power requirements and weight and dimensions for the AFD avionics.

Table 3.5 SFHT Avionics Configuration and Weight Summary

ITEM	AVG. PWR (WATTS)	PEAK PWR (WATTS)	WEIGHT	DIMENSIONS (CUBIC INCHES)
COMPUTER	150	213	40	2808
DISPLAY(3)	15	15	15	427.5
MASS STORAGE	24	24	10.4	300
TOTAL	189	252	65.4	3535.5

The tanker subsystem provides the control and monitoring interface to the tanker subsystems and the satellite. The tanker avionics subsystem is triple redundant and provides two fault tolerance to commanding and monitoring the satellite and safety critical subelements within the tanker. The tanker avionics subsystem will be one fault tolerant to non-safety critical subelements to ensure mission success. Intrafacing will exist between the CPUs for sharing of SFHT and satellite data and CPU housekeeping data. This provides the capability to warn the crew of a CPU malfunction. Power to the tanker subsystem will meet the same requirements as those for the AFD subsystem; i.e., Main Orbiter power for mission success, Aux power for mission safety, and battery backup for Loss-of-Service.

Control and monitoring of the tanker valves and sensors will be performed by electronic units developed for the SHOOT experiment. The Temperature Pressure Measurement System (TPMS) will provide excitation, monitoring, and data processing for the temperature and pressure sensors within the tanker and satellite fluid system. The Heater, Level detector, and Valve control System (HLVS) will provide control and data monitoring for valves and heaters. Both units interface with the tanker CPUs for command and data interactions via a serial link (RS422). The TPMS and HLVS provide the required capability to interface, control and monitor tanker elements. Interfacing to the tanker requires no added hardware (except for cabling), and the units will be flight qualified by the SHOOT experiment. Table 3.6 gives a list of power requirements and weight and dimensions for the tanker avionics.

Table 3.6 SFHT Avionics Power Summary

ITEM	AVG. PWR (WATTS)	PEAK PWR (WATTS)	WEIGHT	DIMENSIONS (CUBIC INCHES)
COMPUTER(3)	60	180	63	3959
PWR DIST UNIT	6	15	26	1620
TPMS	50	50	60	1568
HLVS	60	240	200	5888
THERMOMECH PUMPS	40	40		
MASS GAUGING	40	40		
VALVES		14		
BATTERY			16	240
TOTAL	256	579	365	13275

3.1.6.3 <u>SFHT/OSCRS Avionics Commonality</u> - The SFHT avionics discussed in the previous section were derived from the OSCRS avionics. The two tankers handle different fluids but the requirements on avionics to control and monitor each tanker are similar. Figure 3.26 shows the tanker module AFD and cargo bay package that can remain common for both the OSCRS and SFHT tankers. The common tanker avionics exist from the orbiter AFD to the tanker CPUs. The two block diagrams on the right of the figure show the SFHT and OSCRS add-on modules that will interface with the standard tanker module interface. This part can be considered as an add-on module that completes the tanker avionic system. Common avionics shortens Orbiter crew training and provides an interface that becomes familiar to the crew. Hardware is standardized. Software can be developed in a modular fashion. A common software package can provide control of the common avionics with a software add-on packet that provides commands and data processing and display control that are unique to each tanker.

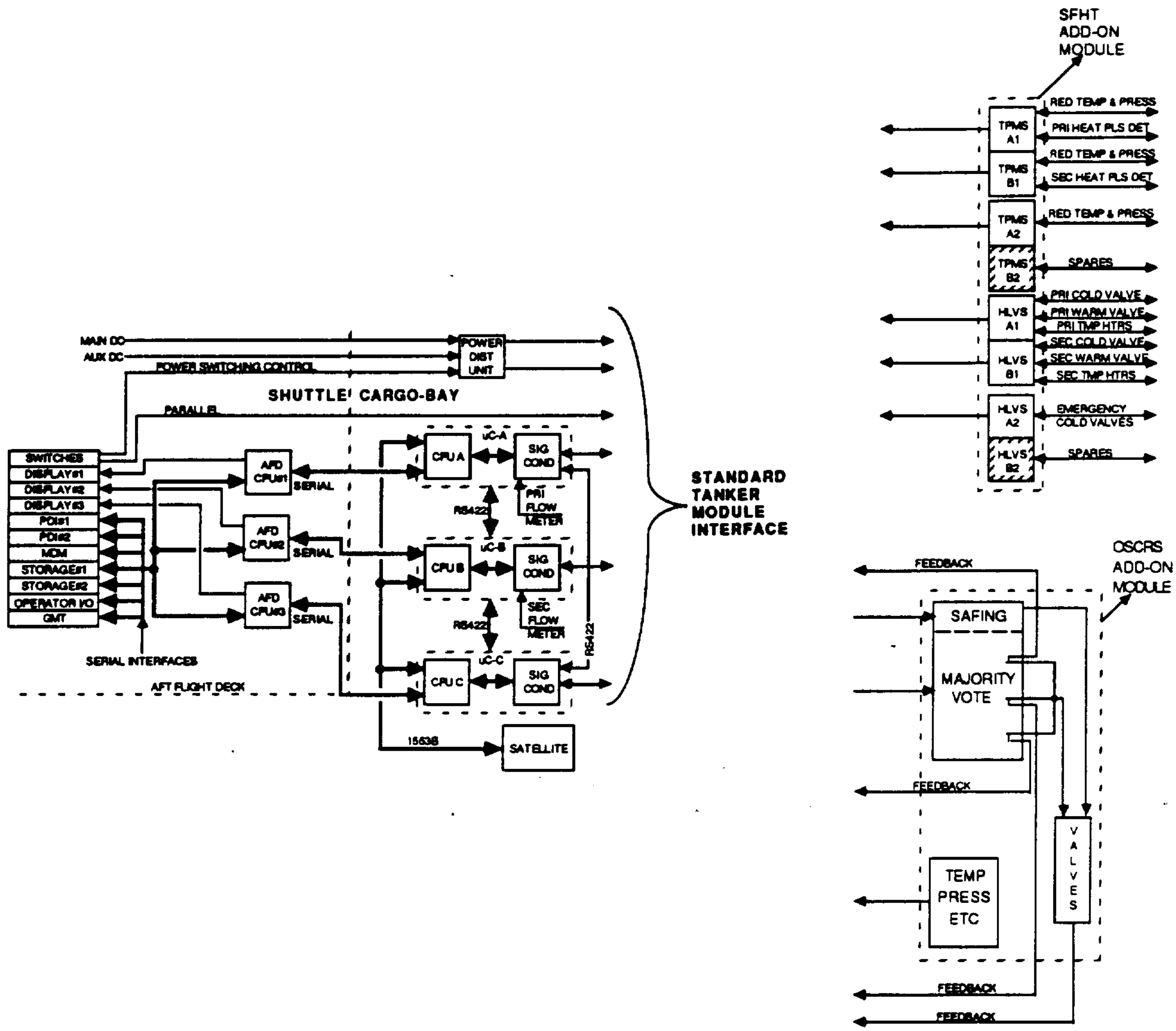


Figure 3.26 SFHT/OSCRS Common Avionics

Since the Challenger accident, NASA-JSC safety and mission integration has reassessed the desirability of having all safety-critical operations be monitored and controlled by the GPC. In Section 3.1.6.5, we address how the overall avionics of the SFHT can be simplified if we use the GPC interface and don't try to maximize commonality with the OSCRS avionics concept. This is possible because the SFHT has a significantly less safety-critical design and operational scenario than does the OSCRS.

3.1.6.4 SFHT-Space Station/OMV Interfaces - In addition to the interfaces with the Orbiter, the tanker must provide the capability of mating to Space Station (truss or MRMS) for commands, data handling, and power. Space Station will replicate the functions of the Orbiter AFD subsystem for controlling and monitoring SFHT during storage and refueling. This requires that the electrical interface between SFHT and Space Station meet the same fault-tolerance and be capable of emulating or matching the same interface between SFHT and the Orbiter, but with minimum impact to the SFHT avionics. For command and data handling at a truss interface, Space Station provides an interface capable of mating with SFHT without changes to the avionics. The interface meets

SFHT two fault-tolerance requirements and provides the same serial link (RS422) that SFHT has with the Orbiter. For power at a truss interface, Space Station provides DC and AC sources with the capability of meeting SFHT fault-tolerance and wattage requirements. Control of power will be via Space Station. Equipment required to provide SFHT with the proper voltage levels will be provided by Space Station control panels and modules. Added circuitry may need to be required by the Power Distribution Unit to allow control of SFHT power by Space Station. When interfacing to the MRMS an electrical interface will be required if a satellite is to be refueled while SFHT is attached. The interface is one fault tolerant to power, and command and data handling. The MRMS provides AC power, so SFHT will need to provide power converters to get DC power.

The control system would be located in either the Service Facility Center or in the laboratory module. Space Station would provide software or use SFHT AFD software to control and monitor the tanker and satellite. Station displays would provide the capability to graphically display data and provide two-fault tolerance.

The OMV interface for command, data handling, and power will be separate from the Orbiter or Space Station interfaces. This is required because of the uniqueness of the OMV interface. Figure 3.27 shows the SFHT-to-OMV interfaces. Power provisions from OMV are one-fault tolerant. Power will be DC, and controlled by the OMV with power protection provided by the tanker. Command and data handling provisions from OMV are two-fault tolerant. This is accomplished utilizing two interfaces that are provided to an attached payload, the Command and Telemetry Data Bus (C&TDB) and the Serial Command and Telemetry Bus (SC&TB); each interface is one-fault tolerant. The SC&TB has a serial interface only, no discrete commands, bilevel, or analog monitoring provided. The C&TDB provides a serial interface, discrete commands, bilevel and analog monitoring capability. To interface to the C&TDB the tanker will be required to provide a Remote Unit (RU). This will add weight and cost to the tanker avionics. An area of concern is when the OMV is performing a maneuver. At this time, no commands or telemetry to and from the tanker will be provided, leaving no insight into tanker status.

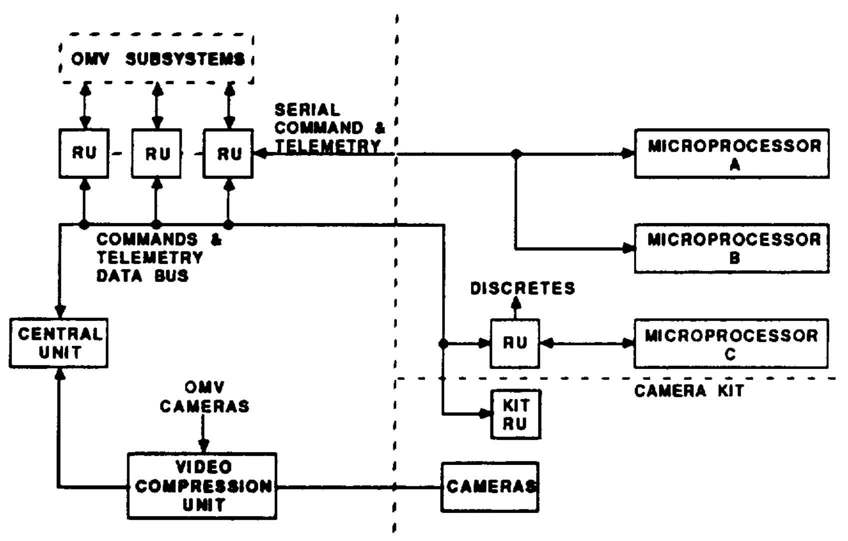


Figure 3.27 SFHT-OMV Avionics Interface

To limit the number of electrical interfaces required for Space Station, it is recommended that the truss I/F utilize the same I/F as that required for the Orbiter. The MRMS & OMV will utilize the same I/F. This will require that the electrical connectors be the same for both the Orbiter/truss I/F, and the MRMS/OMV I/F.

3.1.6.5 SFHT-GPC Interfaces - The orbiter GPC is required to control and monitor any payloads in the cargo bay that are classified as a hazardous payload or have hazardous operations. Any SFHT safety critical control and monitoring would be required to be input through the GPC. The GPC would replace the SFHT AFD control system and interface with the tanker avionics through one of several options. We conducted a trade study of these options and selected the concpet shown in Figure 3.29 as the preferred approach. The GPC has the capability to control and monitor the tanker and satellite in a refueling mission. The GPC provides 40 commands and 40 parameters as a standard payload allocation. Further work is required to determine if these 40 commands and parameters are enough control and insight into the tanker operation to ensure efficient and successful operation of the tanker and satellite.

The tanker interfaces to the GPC via the GPC data bus to Bus Terminal Units (BTU). The data bus is one-fault-tolerant with one bus on the starboard side and one bus on the port side. To maintain two fault-tolerance between the tanker and the GPC three BTUs are required. This will cause a manifest problem because two BTUs are allowed per payload. The GPC communicates with only one BTU when interacting with the tanker. This single interaction may limit insight into the tanker avionics because the crew would have to take for granted that the tanker CPU is functioning properly. This single interaction also adds complexity to the software in the tanker system. The CPU that communicates with the GPC now has to relay commands to the other CPUs as well as collect data to transmit to the GPC. In conclusion, we believe that utilizing the GPC for the SFHT is feasible and will cause minimum impact to the SFHT design (as compared to the impact to OSCRS of using the GPC for all safety critical operations).

3.1.6.6 SFHT Avionics Simplification - The present design of the tanker avionics meets the requirements as stated in the System Requirements Document, Attachment A of the Statement of Work. Due to the characteristics of the superfluid helium tankers, we have complied a number of comments and recommendations regarding updates and changes to the avionics portion of the specification when it is revised. These include:

- TWO-FAULT TOLERANT FOR MISSION SAFETY CRITICAL ITEMS ONLY. The only safety critical items for the avionics are: providing power and control to the pyrotechnic devices, providing two-fault-tolerance to monitoring prior to activation of the emergency disconnect, and providing data to the crew when an EVA is in progress.

- THE AVIONICS SHALL BE CAPABLE OF MEETING SAFETY REQUIREMENTS AND ACCOMPLISHING ALL REQUIRED FUNCTIONS WITHOUT USING ORBITER GPC. The avionics can be simplified if the GPC is used to control and monitor the tanker.

- TWO-FAULT TOLERANT TO PREVENT INADVERTENT OPERATION OF SAFETY CRITICAL VALVES. There are no safety critical valves for the SFHT. Total loss of control of the valves in the worst case will only cause lockup of the Dewar, resulting in pressure rise and relief through the bust discs. The motor driven valves have a 15 to 20 second opening time which reacts too slow to control a safety critical situation. Other tanker subsystems provide two-fault tolerance to controlling safety critical situations.

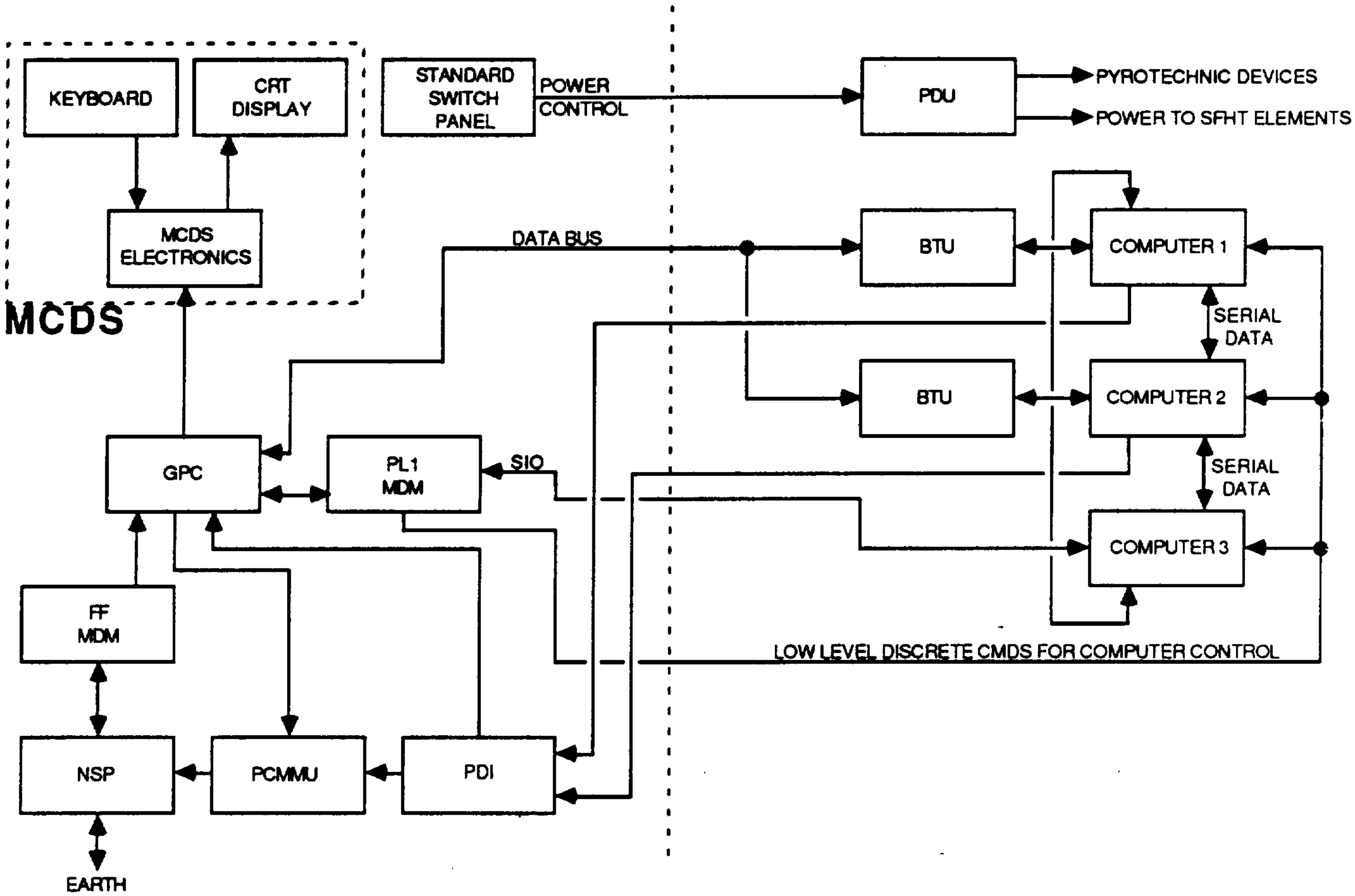


Figure 3.28 SFHT-GPC Avionics Configuration

- TWO-FAULT TOLERANT TO SAFING TANKER AND SPACECRAFT. The tanker provides mechanical two-fault tolerance for maintaining the Dewar in a safe condition in the event of avionics failure. At this time, the interface between the tanker and the satellite is undefined. It is assumed that the satellite fluid system will provide the same mechanical safing as that in the SFHT, thus eliminating the need for two-fault tolerance for safing by the avionics.

- TWO-FAULT TOLERANT TO PROVIDING CAUTION AND WARNING, INDEPENDENT OF THE GPC. Use of the GPC permits a reduction in the AFD control and display system. Data would not be displayed in graphic form, but in tablular form.

- TWO-FAULT TOLERANT TO MONITOR AND CONTROL SAFETY CRITICAL PRESSURE AND TEMPERATURE SENSORS. The avionics will be two-fault tolerant to monitoring safety critical sensors, but the capability to control these parameters may not be possible. The mechanical devices (valves) have an operational time that inhibit controlling any safety critical pressure or temperature.

- GRAPHICALLY DISPLAY SFHT AND SPACECRAFT DATA INDEPENDENT OF THE GPC. The use of the GPC to display data reduces the AFD system when compared to the OSCRS. The GPC does not provide graphic capability; after a failure of the SFHT AFD system, the tanker would be powered down and the GPC would be used for monitoring only.

Figure 3.29 shows a simplified tanker avionics concept. One string of tanker avionics has been removed. The remaining two strings provide one-fault tolerance for mission success. A new design (unit A) would be used if the avionics reduction was limited to the hardware on the tanker. This would not require use of the GPC. A new design (unit B) would be used if the avionics reduction also applies to the AFD system. This removes one AFD CPU and display. Unit B would monitor data and interface to the GPC via the MDM analog channels. The GPC would provide the third link for collecting data and providing it to the crew.

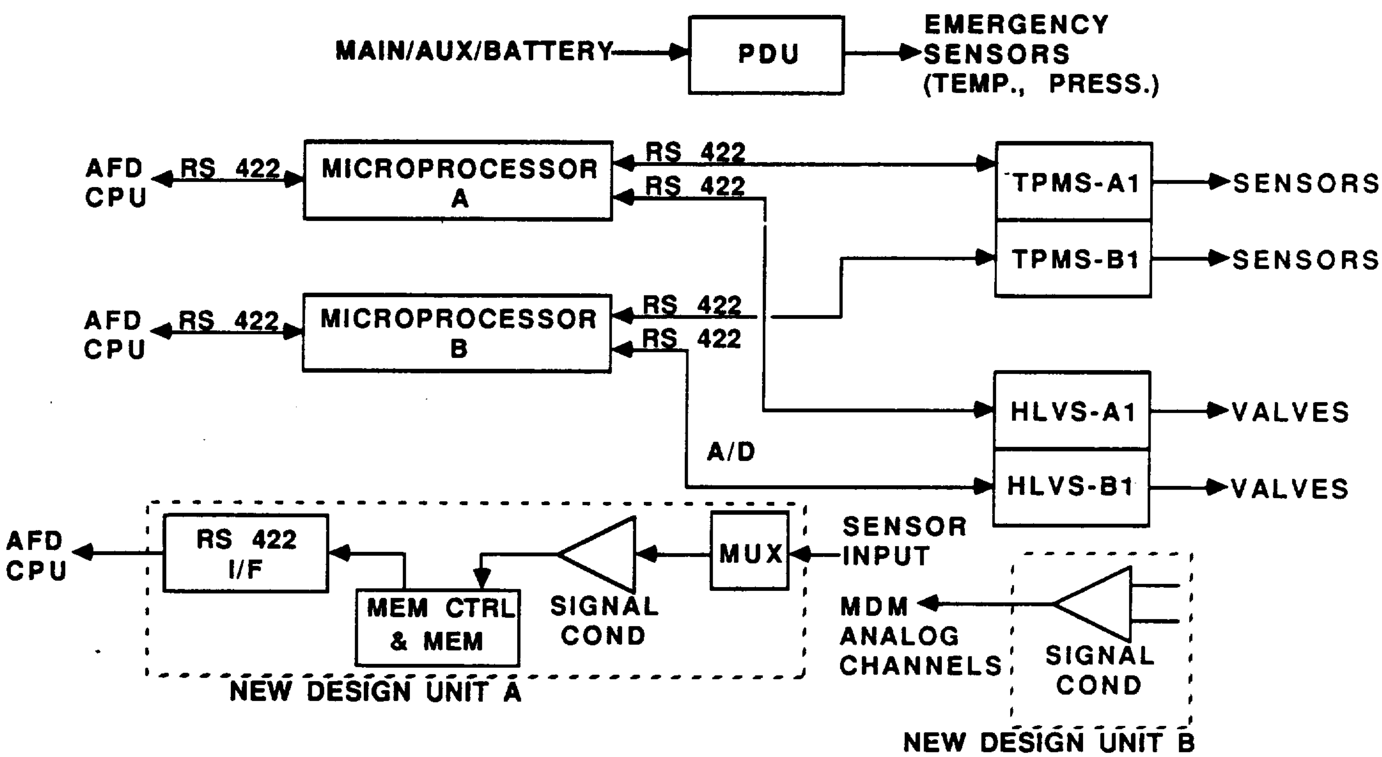


Figure 3.29 SFHT Avionics Simplified Block Diagram

3.2 Facility Requirements and GSE Design

3.2.1 Facilities

3.2.1.1 STS Launch Facilities - Facility capabilities and limitations are an important consideration in the design of the SFHT fluid subsystem and GSE, and the planning of the ground processing flows. Early in the study, our discussions with KSC personnel established some basic groundrules on what facilities could be used to process the SFHT for an STS launch, and these facilites were toured for familiarization. The Payload Hazardous Servicing Facility (PHSF) was identified by KSC as a potential servicing and storage facility for the SFHT. The PHSF is capable of supporting hazardous operations including assembly, testing, propellant transfer, and explosive system operations. It consists of a hazardous operations service high bay connected to an airlock with overhead cranes for handling of payloads. Storage, maintenance, check-out, and helium servicing of the SFHT could be performed in this facility.

The Payload Changeout Room (PCR) at the Shuttle launch pad is a facility designed to install payloads into the Orbiter cargo bay in a protected environment. The Payload Ground Handling Mechanism (PGHM), inside the PCR, is used to insert and access payloads within the cargo bay. The SFHT would be transported vertically to the PCR from the PHSF using the Payload Cannister and Transporter and then inserted into the cargo bay. The SFHT GSE would then be brought to the PCR and placed at the level closest to the SFHT bay location. The layout of the PCR and the relative locations of the PGHM and the Orbiter bay are shown in Figure 3.30.

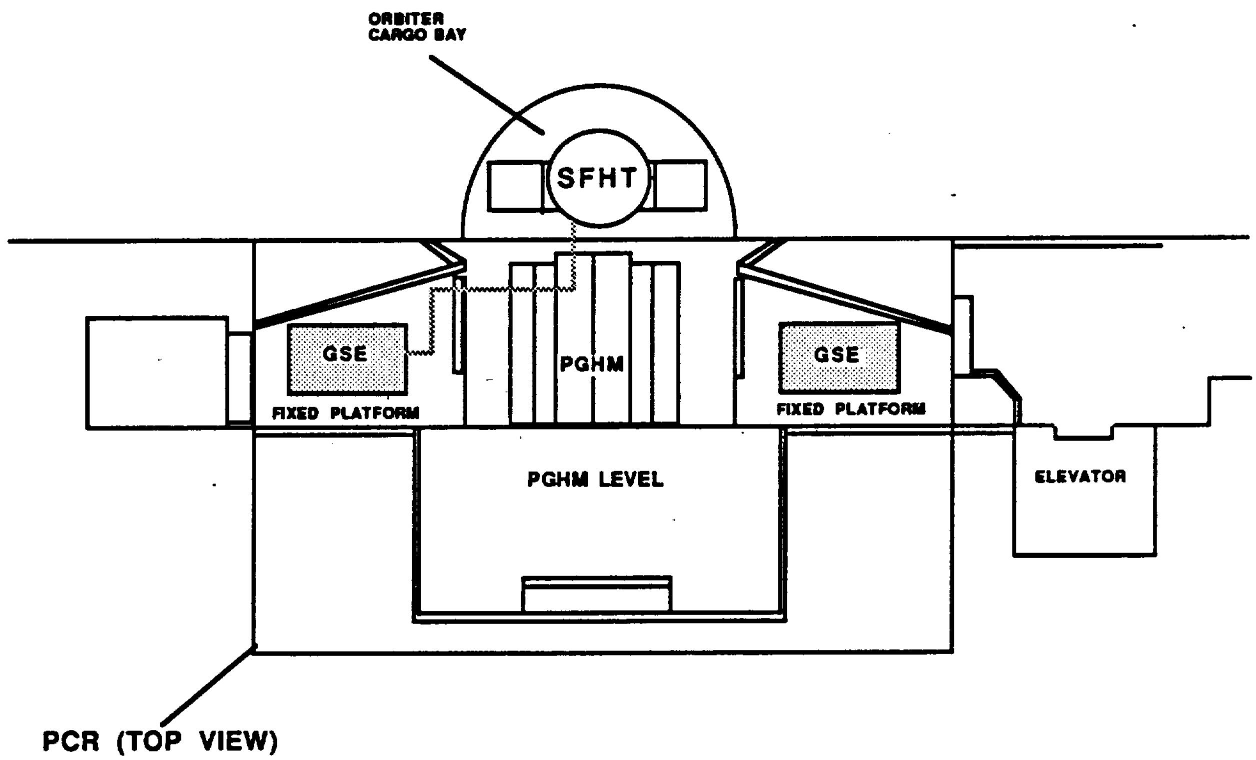


Figure 3-30 Configuration of the Payload Changeout Room Showing SFHT and Associated GSE Relative Locations

One of the more important design considerations for the GSE is its location in the PCR relative to the SFHT. Various options were examined and are summarized in Figure 3.31. The first case shows the GSE located on the fixed platforms on either side of the PGHM. The total distance between theGSE and the SFHT is estimated to be 35-40 feet. The next case has the GSE located on the PGHM providing close access to the SFHT. The drawback with this approach is that the PGHM is limited to ~1500 lbs maximum weight and the GSE weight plus support personnel must not exceed this limit. The third case involves attaching a small GSE supply dewar directly to the SFHT structure to eliminate any helium transfer lines. KSC personnel were consulted for inputs to the three cases (Reference 3.14). The result was that case 1, with GSE located on the PCR fixed

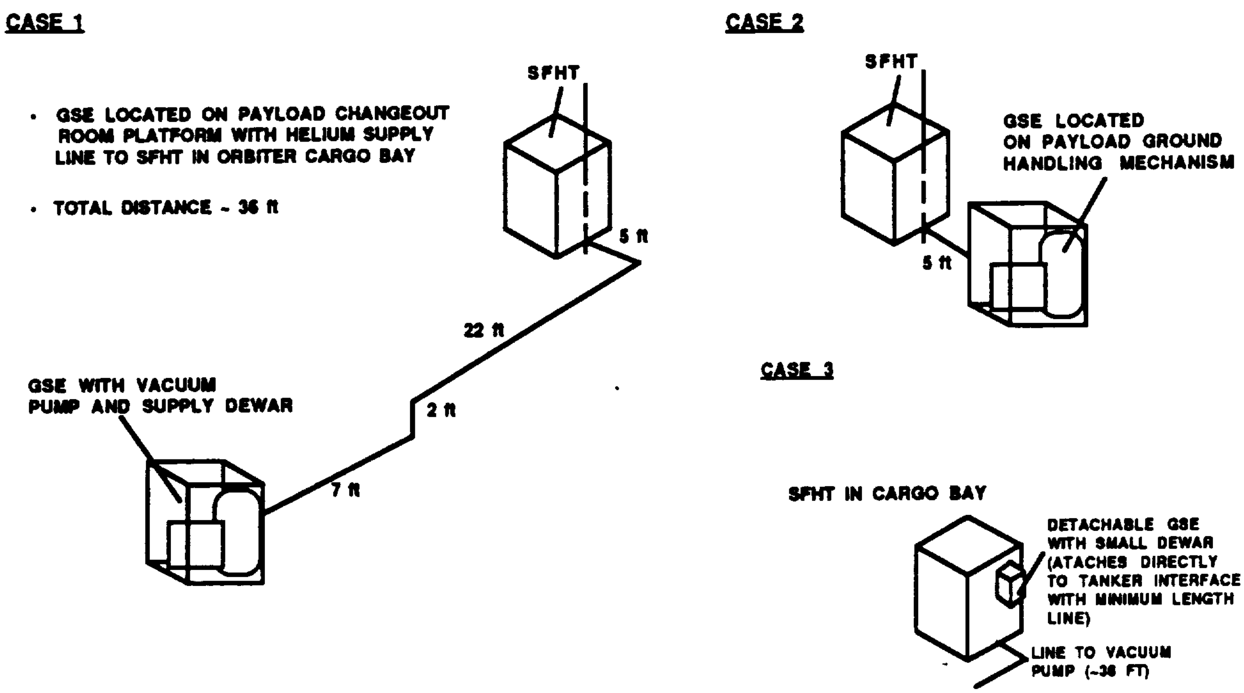


Figure 3.31 Options for GSE Location in The PCR

platforms, is the most likely scenario due to weight and size limitations on the PGHM. Also, it was determined that the GSE with a 750 liter dewar was the largest size that could be accommodated inside the PCR due to the weight limitations of the platforms.

3.2.1.2 ELV Launch Facilities - The launch sites for the various ELV's all have similar accommodations and limitations. For processing of the SFHT, the PHSF could be used regardless of whether the SFHT was being launched on the Shuttle or an ELV. Therefore, the only difference is the accommodations at the launch pad itself. A typical ELV launch pad facility consists of an environmentally controlled work room, work platforms, hoists, and various utility supplies. As with the PCR, there is limited volume for a large amount of payload GSE. However, since the SFHT would be transported to the pad only days before launch (as discussed in Section 3.3.1.2) minimal GSE would be required.

A concept of pad facilites required to support the SFHT is shown in Figure 3.32. Work platforms are provided at various levels to allow access to the SFHT and to support the GSE if it is required. Interfaces for overboard venting to the outside of the environmental shelter will be required, particulary for an emergency vent.

3.2.2 Ground Support Equipment (GSE)

3.2.2.1 Mechanical GSE - Requirements for the SFHT GSE both at the offline facilities and at the launch pads were identified. The mechanical ground support equipment consists of those SFHT unique items (including fluid) that are required to assemble, handle, process, test, and support the in-line and off-line activities of the SFHT flight hardware at the launch site, including payload integration operations with the Orbiter or ELV. Most of this equipment also supports various phases of fabrication, assembly, and test in addition to unique test fixturing and tooling. The mechanical GSE required at the PHSF will be used to cool and initially fill the SFHT. This will be accommplished using normal helium from a trailer. The rest of the mechanical GSE will consist of a

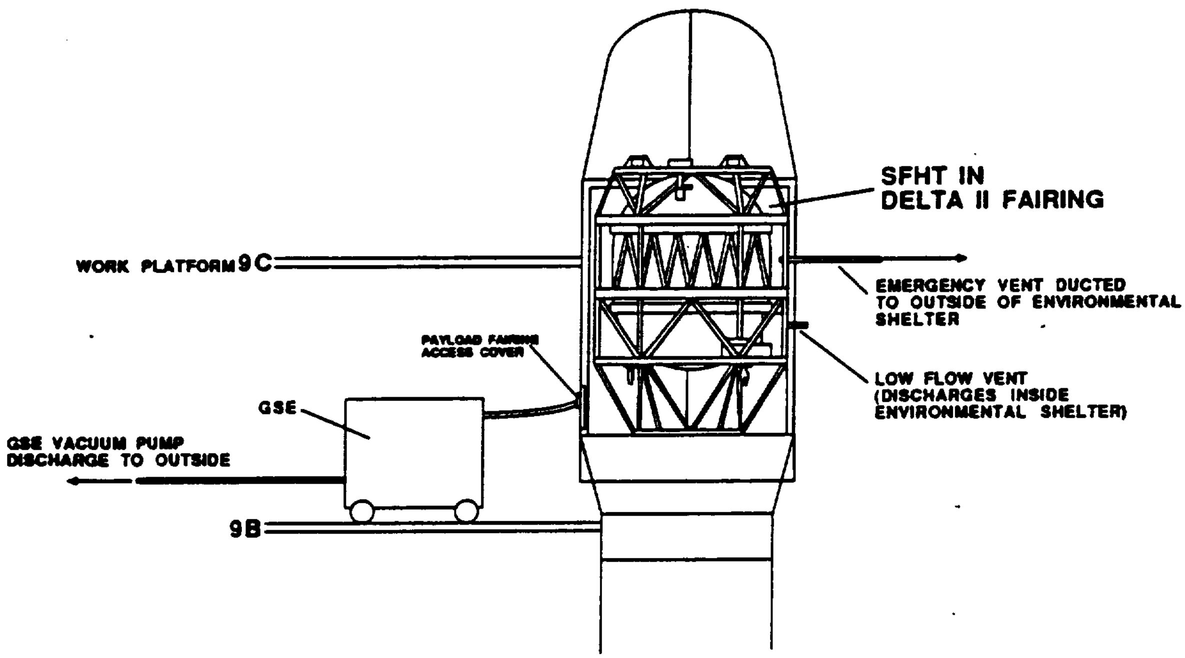


Figure 3.32 ELV Launch Pad Facilities to Support the SFHT

portable liquid helium Dewar with approximately 750 liter capacity along with a vacuum pump. Once the SFHT is filled, thermal conditioning through the internal heat exchanger will begin using the portable GSE Dewar and vacuum pump system. This portable GSE will also be used at the PCR and at the ELV launch site. The GSE Dewar and vacuum pump would be sufficiently small to satisfy the weight and volume constraints of the launch pad facilities.

A list of the MGSE identified for the SFHT is given in Table 3.7. Commonality of the SFHT MGSE with the OSCRS and SIRTF MGSE was assessed to identify potential areas of common development. The helium MGSE, particularly the portable helium supply Dewar, could be shared with SIRTF since the SFHT and SIRTF will have comparable quantities of helium. Similar areas of commonality need to be addressed in future studies.

3.2.2.2 Electrical GSE - The EGSE will be required at the off-line facilities to control and monitor SFHT fluid subsystem valves and instrumentation during system level testing, software development and verification, and prelaunch and post-landing ground servicing. During operations at the pad, however, only those components in the closed-loop thermal conditioning system need to be activated. The EGSE will be capable of simulating all Orbiter-to-SFHT interfaces such as the MDM and PDI, as well as SFHT-to-Spacecraft interfaces. The EGSE will

Table 3.7 SFHT MGSE Required for Processing

ITEM	CATEGORY	DESCRIPTION/FUNCTION
LHe STORAGE/SUPPLY	EXISTING	SEMI-TRAILER NORMAL HELIUM DEWAR FOR CHILLDOWN AND INITIAL FILL
LHe PORTABLE SUPPLY	NEW OR SIRTF SHARED	PORTABLE 750 LITER DEWAR FOR PAD OPERATIONS
VACUUM PUMP	NEW OR SIRTF SHARED	ESTABLISH DEWAR GUARD VACUUM
PORTABLE GSE VACUUM PUMP	NEW	SUPERFLUID CONVERSION THROUGH INTERNAL HEAT EXCHANGER
FLUID SUPPORT KIT	NEW	MISCELLANEOUS COMPONENTS (ADAPTORS, FLEX LINES, Q.D.'s, ETC.)
CALIBRATION KIT	NEW OR SIRTF SHARED	MEETS SFHT UNIQUE SENSOR CALIBRATION NEEDS
GHe PRESSURIZATION	NEW OR OSCRS SHARED	SUPPORTS SFHT PURGING, LEAK CHECKS, AND BLANKET PRESSURE MAINTENANCE
CONTAINER	NEW	PROVIDES FOR ENVIRONMENTAL PROTECTION DURING TRANSPORT, HANDLING, AND STORAGE
SLINGS	NEW OR OSCRS SHARED	USED TO LIFT, ROTATE, AND POSITION THE SFHT IN VERTICAL OR HORIZONTAL DIRECTION
FIXTURES	NEW	ACCOMMODATES SFHT REORIENTATION FROM HORIZONTAL TO VERTICAL AND VISA VERSA
WORKSTANDS/PLATFORMS	NEW OR OSCRS SHARED	PROVIDE ACCESS TO SFHT SERVICE AREAS
MLI STORAGE	NEW OR OSCRS SHARED	PROVIDES FOR STORAGE AND REPAIR CAPABILITY OF BLANKETS

also provide the capability of simulating sensor responses, both within the SFHT and on the spacecraft. Figure 3.33 shows the block diagram. During servicing and deservicing the SFHT flight system in the Shuttle may not be accessible. The EGSE duplicates the flight system to permit control and monitoring of the tanker.

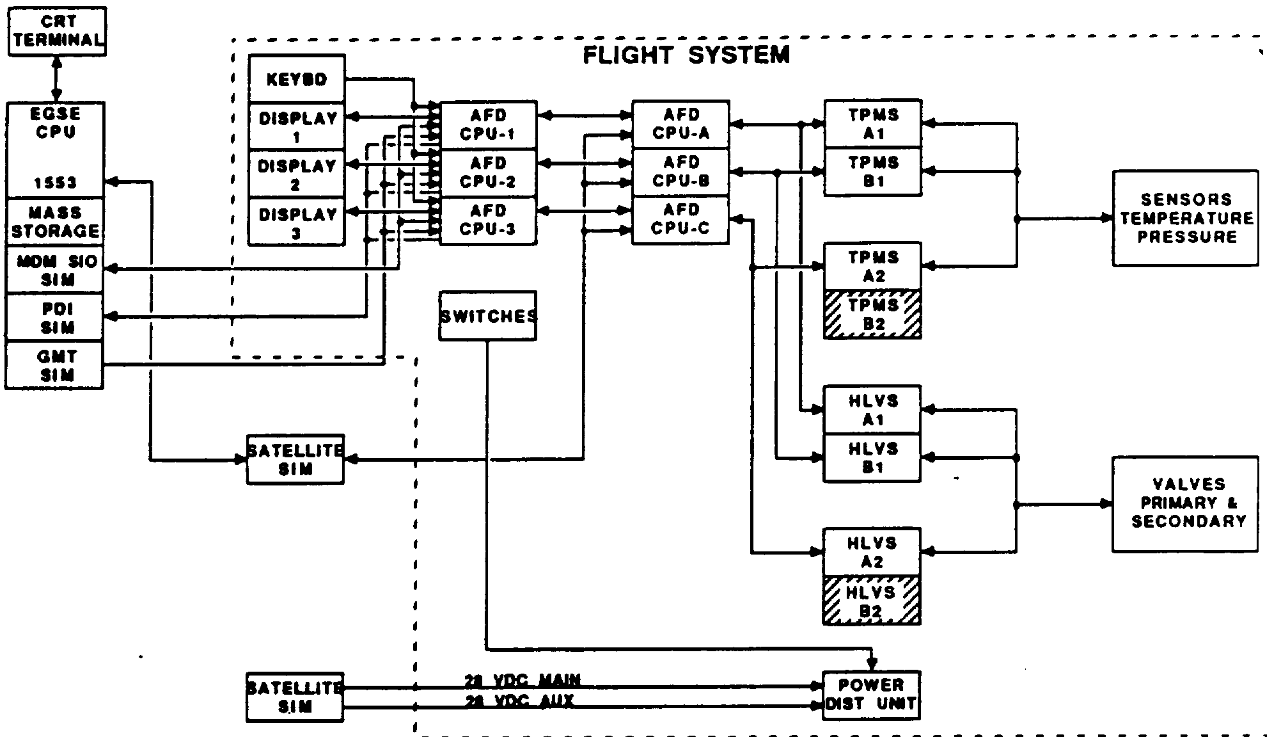


Figure 3.33 Block Diagram of EGSE

During transport operations to the launch pad the ground personnel will need the capability to monitor the condition of the Dewar. This will require a small portable, battery-powered unit that will provide excitation for a limited number of sensors(two temperature, two pressure), to monitor and display the sensor data to the ground personnel as required. The weight of the unit would be approximately five pounds and dimensions approximately 6" X 6" X 4".

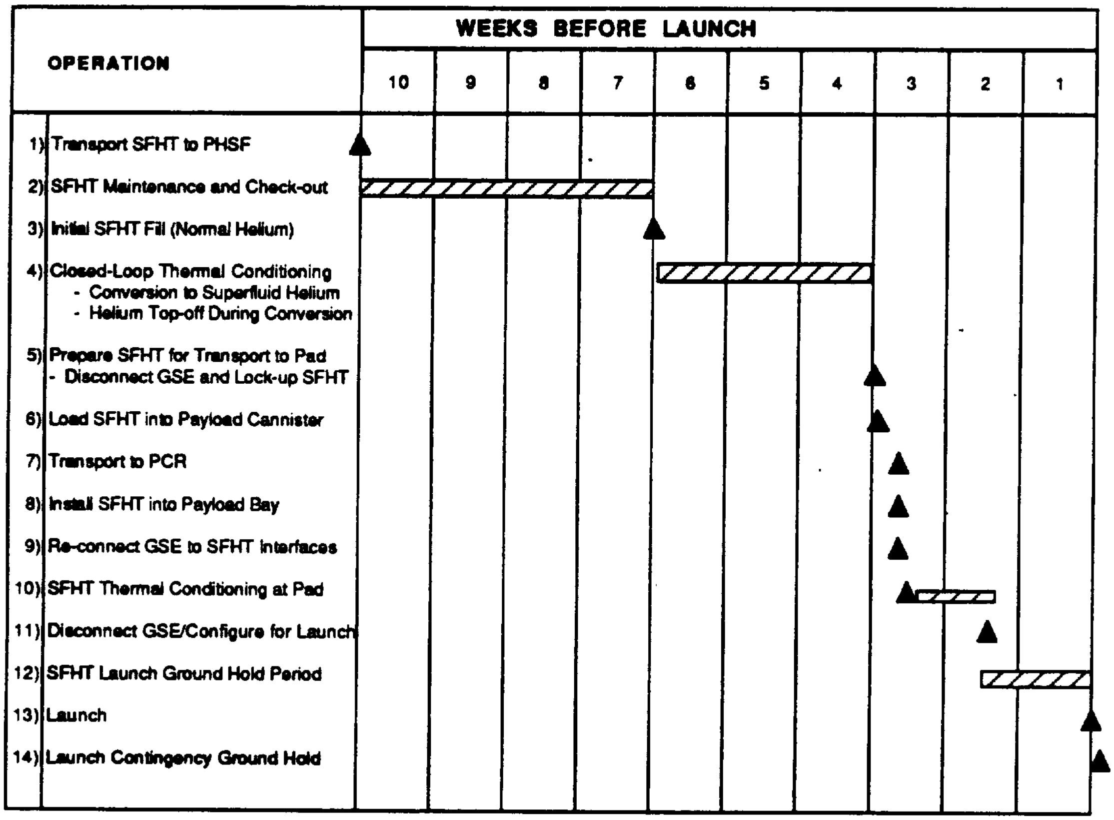
3.3 Operations

3.3.1 Ground Servicing

Ground servicing operations are an important consideration in the design of the SFHT. Limitations both in time and facilities at the launch site are key factors in identifying the requirements for the ground operations. Earlier in the study, we held a meeting with KSC personnel to discuss ground processing scenarios and options for the SFHT for both an ELV and Shuttle launch. Based on this meeting and subsequent conversations, ground operation flows were developed for each of the launch options, identifying timelines, operations steps, and facility requirements. The following sections discuss the results for both Shuttle and ELV launches.

3.3.1.1 SFHT Ground Servicing for STS Launch - The preliminary timeline developed for an STS launch of the SFHT is presented in Table 3.8. The operations begin with the delivery of the SFHT to the Payload Hazardous Servicing Facility (PHSF). The PHSF is capable of supporting hazardous operations including assembly, testing, propellant transfer, and explosive system operations. It consists of a hazardous operations service high bay connected to an airlock with overhead cranes provided for handling of payloads within the facility. Any required maintenance and check-out of the SFHT will be performed in this facility. Four weeks are provided in the timeline for this activity but much more time would be required if components inside the vacuum jacket required replacement.

Table 3.8 SFHT Ground Operations at KSC - STS Launch



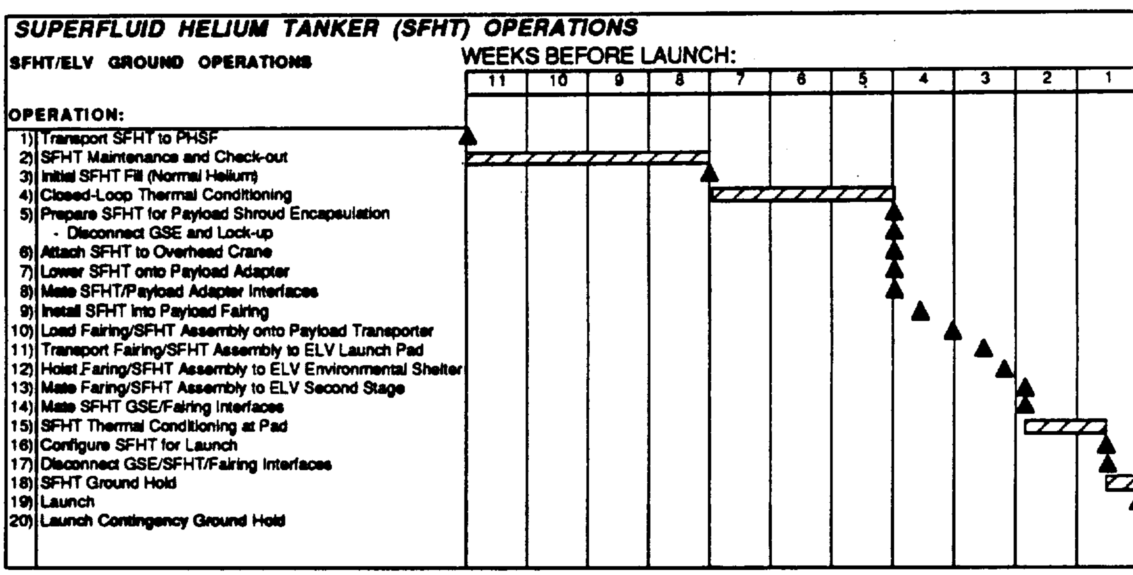
The initial chilldown and fill of the SFHT would occur approximately six weeks before launch. Thermal conditioning and stablization of the Dewar and conversion to superfluid would require about three weeks. The SFHT would then be prepared for transport to the pad in the payload cannister by disconnecting the GSE, locking up the Dewar, and attaching the portable GSE monitoring system (described in Section 3.2.2.2). The SFHT would be placed in the payload cannister and transported to the Payload Changeout Room (PCR) three to four weeks before launch.

Once at the pad, the SFHT/PCR interfaces, consisting of vent lines to the outside, would be connected. These lines are required in the event of an emergency vent should the SFHT be damaged during the process of installing it into the Orbiter. Once installed in the Orbiter cargo bay, the SFHT/Orbiter interfaces, discussed in Section 3.1.2.1, would be mated, the GSE reconnected and thermal conditioning of the SFHT resumed via the internal heat exchanger. Pad thermal conditioning operations would occur during the next eleven days to subcool the superfluid helium, insulation and vapor cooled shields. Ten days prior to launch, the GSE would be disconnected and the SFHT Dewar locked-up and prepared for launch.

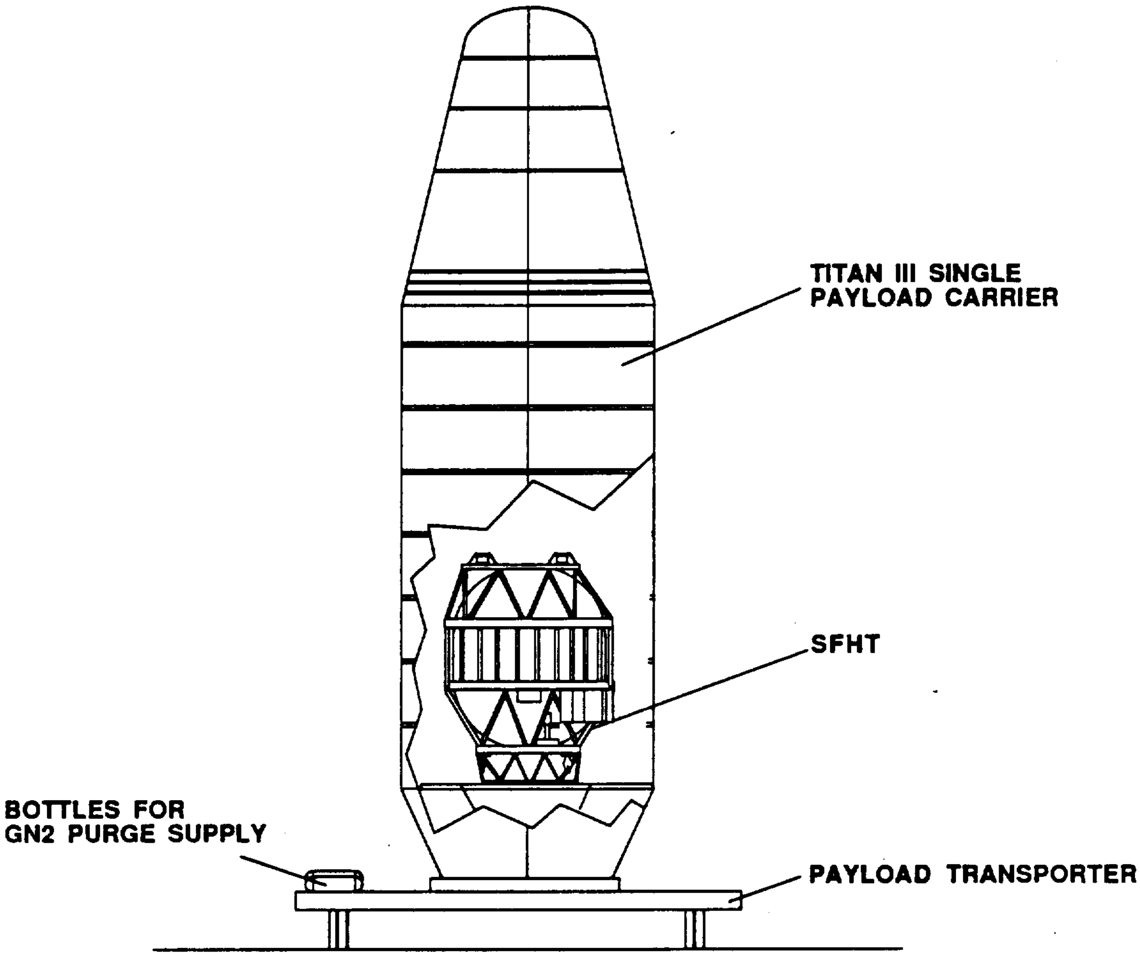
A contingency hold time of 24 hours for a launch scrub is required in addition to the ten day hold. KSC personnel have indicated that the second launch attempt usually occurs 24 hours after the inital launch attempt. The third launch attempt would then occur seven to ten days later due to vehicle recycling procedures. The payload bay doors are normally re-opened during this time allowing access to the SFHT. The GSE would be reconnected and thermal conditioning to subcool the insulation, shields and the superfluid helium would begin, lasting as long as the schedule would allow. The SFHT would be locked up and prepared for the third launch attempt. This procedure would be repeated for subsequent launch attempts.

3.3.1.2 <u>SFHT/ELV Ground Operations</u> - A preliminary ground operations flow for launch of the SFHT on an ELV was developed and is shown in Table 3.9. The PHSF could again be utilized for SFHT maintenance, check-out, and fill as in the STS launch flow. The major difference, however, is that the SFHT can be transported to the ELV launch site approximately 3 to 4 days before launch rather than the 3 to 4 weeks required for an STS launch. SFHT transport operations would begin by bringing either the ELV payload fairing (Atlas and Titan launches) or a transport cannister (Delta launch) to the PHSF. The SFHT would be installed and the interfaces with the fairing mated. The SFHT assembly would be loaded onto the ELV payload transporter and taken to the pad. The SFHT transport configuration is shown in Figure 3.34 for both the cannister and fairing installation options. Regardless of the particular ELV, a nitrogen purge and limited power is provided to the payload to maintain conditions during the transport process.

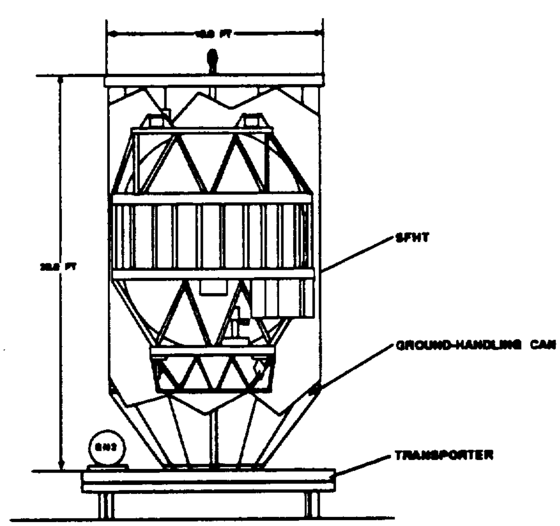
Table 3.9 SFHT Ground Operations - ELV Launch



Once at the pad, the fairing or cannister is hoisted to the environmental shelter area surrounding the launch vehicle where work platforms and other equipment for mating the payload to the launch vehicle are provided. The SFHT is then mated to the ELV second stage and all utility connections are mated. The benefit of the ELV launch flow is that, since the SFHT is taken to the pad only 3 to 4 days before launch, no thermal conditioning should be required as the Dewar can remain locked-up during this time. However, in the event of extended launch scrubs, GSE would be required to



a) SFHT in Titan III Payload Shroud/Transporter



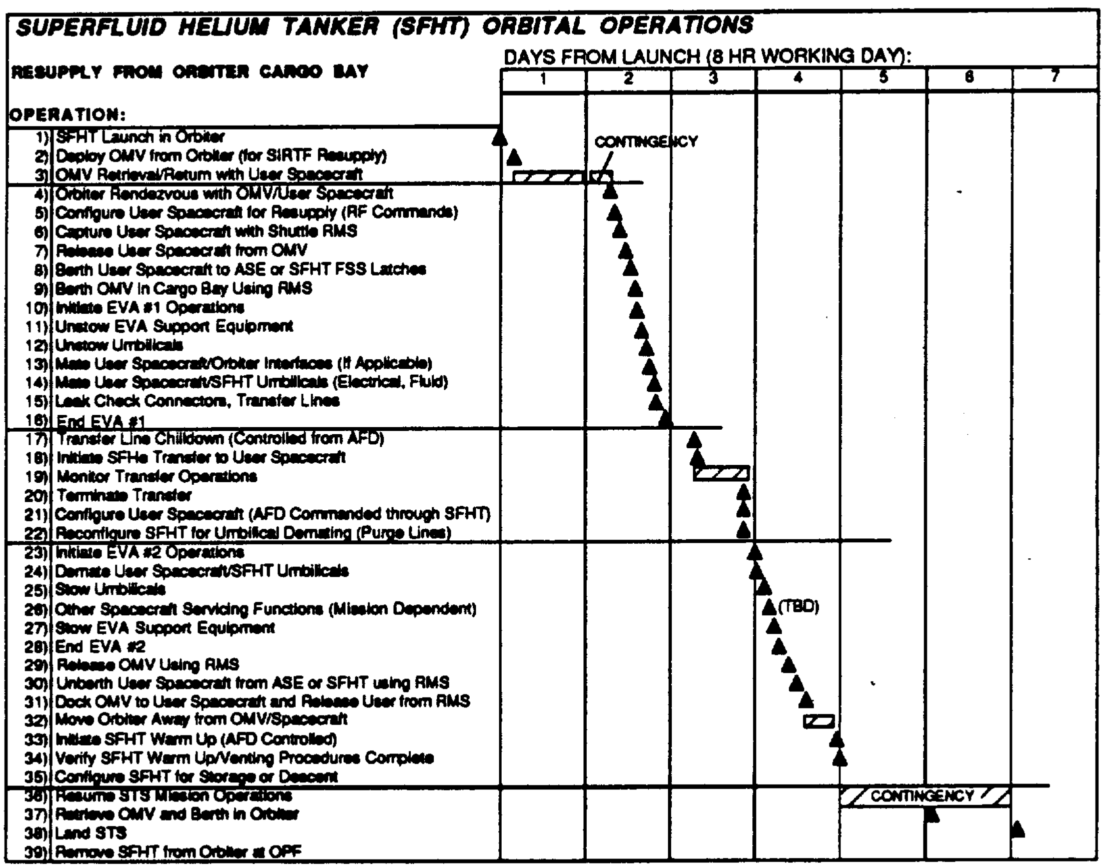
b) SFHT in Delta Payload Ground-Handling Canister/Transporter

Figure 3.34 SFHT Transport Options for ELV Launch Mode thermally condition the insulation, shields, and superfluid helium via the closed-loop heat exchanger. This requires appropriate interfaces in the payload fairing to allow the GSE to connect to the SFHT ground service panel.

3.3.2 Ascent and On-Orbit Operations

3.3.2.1 SFHT/STS Operations - An operational flow for SFHT helium on-orbit replenishment operations from the Orbiter cargo bay was developed to identify EVA requirements and timelines. The timeline is presented in Table 3.10 with the operations listed sequentially with their corresponding time intervals based on 8 hour working days. The timeline was generated around a SIRTF type resupply mission where the OMV and the SFHT are launched simultaneously along with a berthing mechanism such as the A' cradle.

Table 3.10 SFHT Orbital Operations from Orbiter Cargo Bay



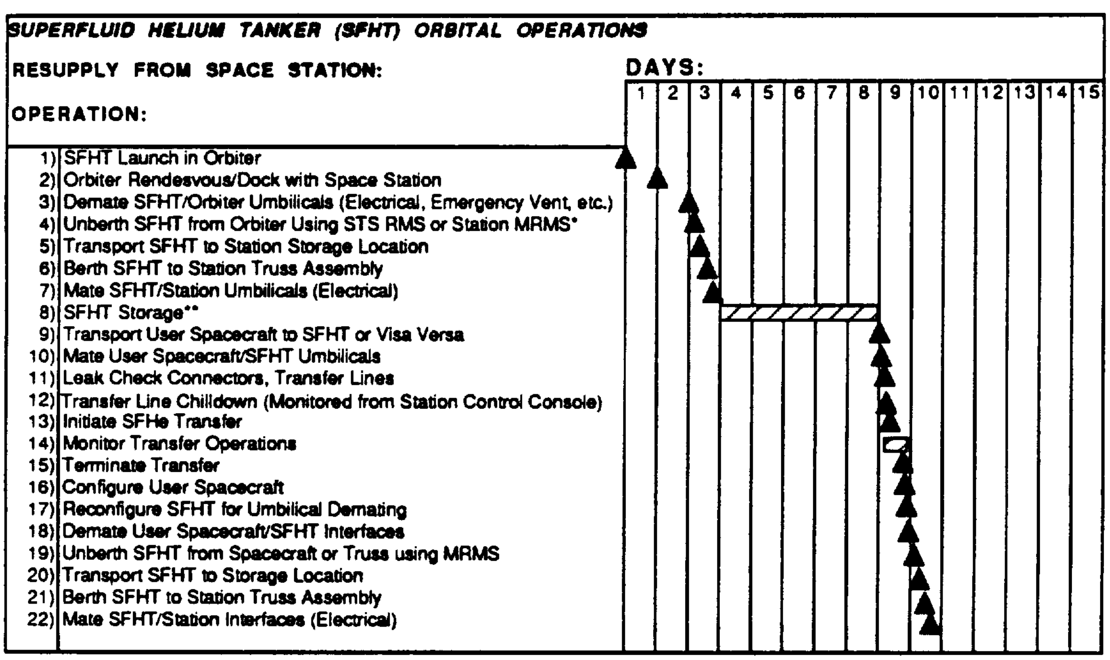
After reaching orbit, the OMV is deployed on the first day of the mission to retrieve the SIRTF from its operating orbit. Various studies including the STICCR studies have estimated the time for the OMV to retrieve and return with the SIRTF to the Shuttle orbit as 16 hours. OMV rendezvous with the Orbiter occurs on the second day, and capturing and berthing of the user spacecraft and the OMV is performed using the Shuttle RMS. Any reconfiguring of the user spacecraft subsystems could also be performed at this time. Contingency was included in the second day's timeline to account for problems in the OMV retrieval phase. An EVA would be initiated after the OMV and the user spacecraft are berthed in the Orbiter to unstow and mate the fluid and electrical couplers. The helium couplers would then be leak checked to ensure a proper connection. Any other spacecraft servicing functions could be performed after this during the remainder of the six hour EVA.

Helium transfer operations would be initiated on day 3 via the Aft Flight Deck control station. The third day would also be used as a rest day for the EVA crewmembers. When transfer operations are complete, both the SFHT and user spacecraft would be configured for umbilical demating. This involves venting of the transfer lines to space to remove the helium. Due to helium's low vapor pressure and the long length of the lines, this venting operation would take place during the sleep period. Also, adequate time is needed for line warm-up prior to EVA disconnections and stowage.

On the second EVA on day 4, the couplers would be demated and the transfer lines stowed. Any other EVA tasks required to prepare the user spacecraft for deberthing would be performed and the EVA ended. The RMS would then deploy the OMV and deberth the user spacecraft. The user spacecraft would remain attached to the RMS for OMV docking and then released. The OMV would begin the transport of the user spacecraft to its operating orbit. The SFHT would then be configured for storage and descent from the aft flight deck control station. Two days would remain for contingency and OMV retrieval assuming a normal seven day mission.

3.3.2.2 SFHT/Space Station Operations - Operations of the SFHT at the Space Station will involve long orbital stay times. Resupply of small laboratory experiments will take place frequently, but replenishment of large users such as Astromag and SIRTF will be done at approximately two year intervals. The SFHT can be launched to the Station on either the Shuttle or ELV. If launched on an ELV, retrieval of the SFHT by the OMV will be required. For a Shuttle launch, the SFHT will be removed from the payload bay sometime during the 5 to 7 day stay time at the Station. The SFHT/Orbiter interfaces would be demated and the Station MRMS would then grapple the SFHT and transport it to its storage location, either on the truss or in or near the Servicing Facility when it is in place. The SFHT storage period before performing a large user resupply such as SIRTF, could be 90 days. The user spacecraft would be transported to the SFHT (or visa versa) and the fluid and electrical interfaces mated. From this point, the helium transfer operations are the same as an STS-based operation. After completion of the transfer operations, the SFHT would be demated from the user and returned to its storage location on the truss. A representative resupply timeline when servicing at the Space Station is shown in Table 3.11.

Table 3.11 SFHT Orbital Operations When Servicing From Space Station



* COULD BE 5 DAYS UNTIL SFHT IS UNLOADED FROM ORBITER CARGO BAY
** UP TO 90 DAYS

3.3.2.3 <u>SFHT/ELV Orbital Operations</u> - Launch of the SFHT on an ELV requires that the ELV place the SFHT in a stable orbit within reach of either the OMV or the Orbiter for retrieval. The operational flow for these orbital operations is presented in Table 3.12. The SFHT would remain attached to the ELV second stage after the desired parking orbit is reached. Second stages of the Delta II and Titan III provide limited three-axis stablization capability as does the Centaur upper stage. The Titan IV currently does not have any capability to stablize payloads for deployment in low earth orbit. The OMV would then rendezvous with the ELV second stage and dock with the front face of the SFHT which would be equipped with FSS "towel" bars to mate with the OMV's

Table 3.12 SFHT Orbital Operations for ELV Launch

SUPERFLUID HELIUM TANKER (SFHT) OPERATIONS									
SFHT/ELV ORBITAL OPERATIONS		HOURS AFTER LAUNCH:							
		1	2	3	4	5	6	7	8
OPERATION:									
1)	Parking Orbit Insertion and Trim Burn								
2)	Establish Three Axis Stabilized Mode								
3)	OMV Rendezvous with ELV 2nd Stage								
4)	Dock OMV to SFHT								
5)	Deploy SFHT from ELV 2nd Stage								
6)	ELV Stage 2 Separation Manuever								
7)	SFHT Transport to User/Space Station by OMV								

TPDM, as shown in Figure 3.35. The explosive bolts on the SFHT's adapter structure would then be fired to separate the SFHT from the ELV. The OMV would subsequently transport the SFHT to the Space Station or to the user orbital location for in-situ resupply operations.

3.3.3 <u>Descent and Post-Landing Operations</u>

SFHT on-orbit operations, under normal conditions, will result in the SFHT being returned to the ground empty. For the case where the SFHT is used as a supply depot at the Space Station, the SFHT will likely be empty upon being returned to the ground since it is being changed-out with a full SFHT. For STS-based resupply, the SFHT should be empty or nearly empty if SIRTF is the user spacecraft. Upon completing the final helium transfer operation on-orbit, the SFHT will besafed by venting the Dewar to space and allowing it to warm-up. Therefore, under normal conditions, the SFHT post-landing operations would be relatively simple, involving only removal of the SFHT at the Orbiter Processing Facility (OPF) and transporting it to the PHSF. Contingency situations, however, where the SFHT returns to the ground with helium remaining could result in involved post landing operations, as discussed in the next section.

3.3.4 <u>Contingency and Abort Operations</u>

The SFHT can either be partially full of helium or completely empty upon completion of a helum resupply operation, depending on the user being serviced. In all cases, however, it is desirable to return the SFHT to the ground empty to avoid creating a situtation where the burst disks need to rupture to relieve pressure. Apart from the potential hazards resulting from such a vent, extended maintenance operations would be necesassry to replace the burst disks since some are located inside the vacuum jacket of the SFHT Dewar.

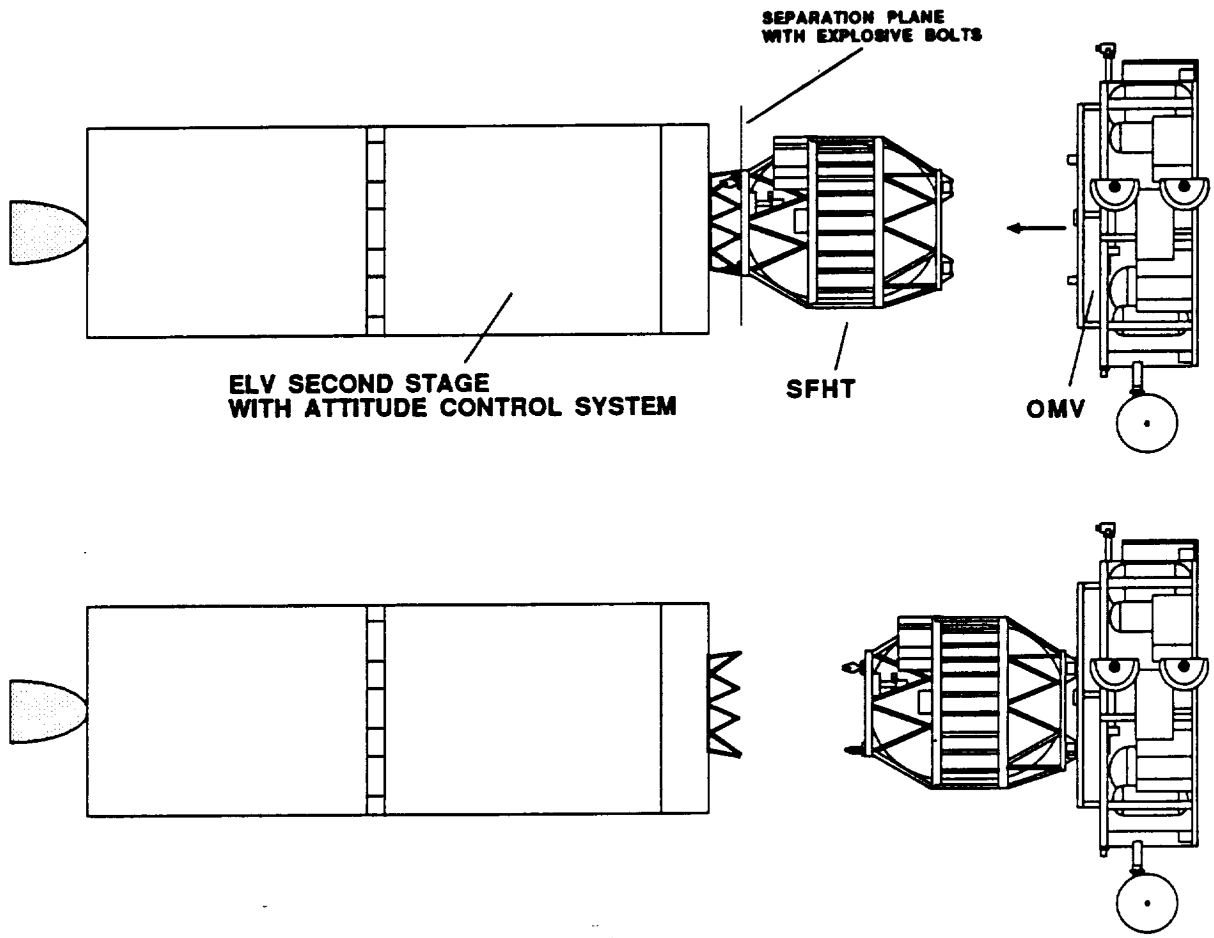


Figure 3.35 Transfer of SFHT From the ELV to the OMV

The SFHT could return to the ground with a full or partial load of helium due to several contingenies. A Return to Launch Site (RTLS) abort results in the SFHT landing with a full load of helium while still in the Orbiter cargo bay. In this case, access to the SFHT is not possible and the emergency vent system with the redundant burst disks ensures that the SFHT will be able to relieve any excessive pressure buildup. Personnel and equipment would have to avoid the vent discharge, however, to prevent a hazardous situation. The Orbiter would then be towed to the OPF and the SFHT removed after a relatively short period.

Once removed from the Orbiter, it is desirable to drain the SFHT as quickly as possible to avoid an emergency venting case. After connecting the SFHT and determining the temperature and pressure conditions inside the Dewar, the SFHT would be drained by connecting to the ground fill port and pressurizing the tank to above atmospheric pressure using gaseous helium if required. The helium would then be drained through the fill line. Depending on the conditions inside the Dewar, this drain process could take place either in the OPF or the PHSF.

The RTLS abort returns the Orbiter to KSC relatively quickly and therefore the SFHT could be removed from the bay in a fairly short time period. However, an abort to a contingency landing site, either from a transatlantic abort or an emergency return from orbit, would mean that no access to the SFHT would be possible for as long as several weeks until the Orbiter is returned to the OPF, since the payload bay doors cannot be opened and supported without external equipment. The SFHT could be full of helium in the bay for this time and the emergency vent system would be the only method of reducing pressure. The only alternative would be to provide an SFHT/Orbiter fill/drain interface to allow the SFHT to be drained with the Orbiter horizontal and the payload bay doors closed. This requirement needs further examination since it would be major impact to the SFHT fluid subsystem and the GSE.

3.3.5 Ferry Flight Operations

Ferry flight operations for a normal SFHT mission would not require any significant preparation procedures since the SFHT would be empty or nearly empty. However, the contingency situations, described in the previous section, would require the SFHT to be transported while still full of helium. Again, the emergency vent system is in place should an excessive pressure build-up occur. It would be desirable, however, to monitor the SFHT Dewar conditions during the ferry flight to determine if the pressure and temperature within the Dewar are staying within non-vented condition limits. Power to the on-board avionics would be required, or the battery-powered portable GSE monitoring system could be left attached to the SFHT, to provide a limited monitoring capability without the need for vehicle power.

3.4 SYSTEM SAFETY

The Superfluid Helium Tanker (SFHT) is being designed to meet the requirements of both manned and unmanned launch systems. The requirements for design are stipulated in NHB 1700.7B for manned systems and ESMC 127-1 for unmanned ELVs. The design requirements, specifically as they address the degree of fault tolerance, for manned systems are the primary driver except for ordnance and pyrotechnics systems. In the area of range safety and launch operations, the ESMC 127-1 document is the primary driver because these requirements are more stringent.

The following paragraphs discuss the requirements of NHB 1700.7B which are considered to be the most critical to the design of the SFHT. It must be indicated that these requirements are not firm requirements since the NHB 1700.7B document is not an approved document and that some changes to the text may be forth coming. However, it is a good indication of the direction safety requirements and design implementation is heading and allows us to make preliminary safety assessments of our design concepts. The safety provisions for our baseline design have been factored into the various subsystem designs and are discussed in their respective sections. The flight and ground safety discussions below highlight several of the major safety drivers for both the ELV and STS launch options.

3.4.1 Flight Safety

There is one design issue that is being driven by ELV launch. ESMC Range Safety is requiring destruct capabilities in the event of an aborted mission for payloads which contain large Dewars. There is at this point no distinction between Dewars which contain liquids such as LO_2/LH_2 versus Dewars which contain liquids such as LN_2 or LHe. Some ELVs are providing the destruct capabilities as a service to the payload organization. This service is desirable to prevent destruct hardware from being placed on the SFHT itself. This requirement could greatly increase the complexity for redundancy and safing verification, especially for mission scenarios in which the SFHT is to be launched by an ELV and retrieved by the Space Shuttle.

In the evaluation of the SFHT to NHB 1700.7B requirements, there is only one SFHT design element that has been identified as being safety critical. This design element is the electrical shutdown of the superfluid helium pump. The identification of the helium pump as safety critical necessitates the requirement that the pump electrical system be two-fault tolerant to terminating the electrical power to the pump unit. The identification of the pump electrical power circuit as being safety critical is to provide sufficient fault tolerances to prevent superfluid helium from being flowed into its associated transfer line in the event of an emergency with the Orbiter or the receiving satellite vehicle.

Since we cannot assume we can use Orbiter power in the event of an Orbiter emergency requiring that we separate the user spacecraft from the SFHT, we have added a battery to provide power for firing the pyrotechnics used to operate the emergency disconnect. We will need to monitor the status of valves and pump heater power prior to activating the emergency disconnect so that we don't dump a large quantity of liquid helium in the cargo bay. The monitoring of these critical components will be done through use of the Orbiter GPC.

3.4.2 Ground Safety

In the evaluation of the SFHT ground processing flow to the requirements of ESMC 127-1 and KHB 1700.7A, three ground processing safety concerns were identified: 1) emergency venting in the PHSF during SFHT fill operations, 2) emergency venting while the SFHT is being transported to the pad, and 3) emergency venting in the PCR. Special vent lines and procedures will be provided to assure that during the entire ground processing, once the Dewar is loaded with liquid helium, safe Dewar venting could occur.

4.0 TASK 4 - COMMONALITY ASSESSMENT AND TECHNOLOGY DEVELOPMENT RECOMMENDATIONS

The initial subtask of Task 4 was to assess SFHT design and operational commonality with other subcritical/supercritical cryogen tankers. This task was de-emphasized at the beginning of the program, so we only did a quick review of the SFHT design to identify those elements that might be usable as part of a non-helium cryogenic tanker. Some of the concepts and modelling tools for Dewar thermal optimization might be usable but must be used with the appropriate databases for the fluids under consideration. The vent system (e.g., porous plugs) for the SFHe is of course unique to liquid helium and the flow analysis involves two-fluid models and identification of flow regimes where the fluid behaves as a "Quantum" fluid or a "Newtonian" fluid. Design of components, such as valves and the transfer line coupler, suggest approaches for low heat leak but would need a thorough review of the safety aspects, particularly for cryogens such as liquid hydrogen and liquid oxygen. For example, the liquid helium valve being designed by Utah State would not be acceptable for hydrogen usage since hydrogen in and around the stepper motor could lead to fire and explosion.

Our overall assessment of commonality potential is that there is little that is directly transferrable to other cryogenic tankers, particularly in the fluid subsystem. The OSCRS avionics subsystem might have a fair amount of commonality; due to the safety issues with liquid hydrogen and liquid oxygen, however, the avionics redundancy and fault-tolerance would be closer to OSCRS than to the avionics for the SFHT, which is not that safety critical.

In evaluating technology needs, we looked at both those items being developed on SHOOT, and those tanker-specific items not being developed in SHOOT. In some cases, those items being developed on SHOOT require additional testing for 50 missions usage or to design limits beyond those used on the experiment test bed. Table 4.1 is a brief summary of the technology development being pursued for SHOOT. Table 4.2 contains our listing of development needs not being addressed by SHOOT. A technology development program schedule and cost estimate to accomplish each will be included in our separate cost document submitted with the final report.

Table 4.1 SHOOT Mission Technology Development

Demonstrate:

- Liquid Helium Transfer Using TM Pump
  - 50 L/Hr (Goal of 800 L/Hr)
- Fluid Containment Techniques
  - During Normal Storage and Cooldown of Receiver
  - During High Flow Rate Transfer
- Fluid Acquisition System
  - 500 L/Hr (Goal of 800 L/Hr)
- Mass Gauging and Flow Measurement Techniques
  - Heat Pulse
  - Superconducting Wire (With Settling)
  - Venturi Flowmeter
- EVA Transfer Line Coupler On-Orbit Operation
  - (Use of GRiD Computer; Interface with Orbiter GPC)

Table 4.2 Technology Development Needs Not Being Addressed by SHOOT

- Superfluid Helium TM Pump Performance
  - 500 to 1000 L/Hr
- Transfer Line Characterization (Heat Leak Critical)
  - Flex Lines
  - Line Lengths to 15 Feet
  - EVA Compatibility (Including Couplings)
  - Emergency Disconnect Compatibility
  - Two Phase Flow During Transfer (How to Suppress, if Needed)
- High Conductance Valves
  - Handle Fluid Transfer Rates to 1000 L/Hr
  - Reduced Weight
  - Good for 50 Mission Life
- Motorized Throttling Valve
  - LHe Temperatures
  - Use as Thermal Conditioning (JT Valve)
  - Use for High Rate Venting During Transfer
- Transfer Line Coupling
  - Qualifying for 50 Missions
- Porous Plug Phase Separators
  - High Capacity Porous Plug Phase Separators for Venting During Transfer
  - Characterization of Normal Vent Porous Plug Phase Separator (Controllability, Flooding, Efficiency as Thermodynamic Vent Element)
- Selection/Characterization of Conventional Insulation on Large Tank
  - K vs T
  - Outgassing
  - Ability to Withstand Thermal Shock
  - Use of Reflective Surface (e.g. Tape) or Other Options Such as Direct Aluminum Layer Application
- MLI Blanket Fabrication Technology for Between Flight Maintenance
  - Dewar Component Changeout Considerations
  - Blanket Edge Fabrication and Performance
- Dewar Ground Operations Heat Exchanger Characterization
  - Internal Heat Exchanger Sizing and Design to Condition and Maintain Stored SFHe at Desired State Without Topping
- Dewar Design/Fabrication Technology
  - Structural Design Approach (Supports Piercing Into Inner Vessel)
  - Stiffness of Telescoped Tank Support
  - Effective Thermal Conductance of Telescoped Tank Support System; Thermal Cross-Coupling)
  - Insulation on Inner Vessel to Minimize Emergency Vent Line Size
  - VCS/Heat Exchanger Fabrication and Thermal Optimization
  - Alumina-Epoxy Straps for Large Dewars
    - Cycle Life To Meet 50 Mission Requirement
    - Thermal Performance
- Slosh
  - Design Concern?
  - Impact to Liquid Acquisition Device?
- Liquid Acquisition Device
  - Two-Fluid Flow
  - Pumping to Refill
- Limited Life Avionics Parts
  - Identification of Piece Parts That May Not Withstand 50 Missions (Examples: Switches, Relays, Motors, Solenoids)
  - Conduct Qual Tests To S Level to Impove Life
- Evaluate TPMS and HLV for 50 Mission Usage
  - Evaluate Reliability of Piece Parts
  - Examine Repackaging to Increase Reliability

5.0 TASK 5 - PROGRAM PLAN FOR SFHT DEVELOPMENT

We prepared a program plan for the SFHT development which addressed our approach to the detailed design and development, fabrication and test of the superfluid helium tanker. The phase C/D program as outlined runs through post-flight analysis of the first mission and is 6 years in length, ending with a launch in October 1997. The program plan, master program schedule and work breakdown structure are addressed in the following paragraphs. A few of the groundrules associated with our program cost estimate we've developed will be submitted as a separate volume of our final report.

5.1 PROGRAM PLAN

The program plan addresses detailed design, fabrication and test of the conceptual superfluid helium tanker design prepared during Task 3. The SFHT is designed to meet the requirements of the Systems Requirements Document, Attachment A to the contract SOW. The program consists of detailed design of both the flight equipment and GSE, fabrication and test of a dedicated Dewar Qual article to verify the multimission life capability, fabrication of one flight unit and one set of GSE, testing, delivery to NASA-KSC and support of the mission. We believe that eventually, a second superfluid helium tanker would be procured as a backup capability or to permit one tanker to be used as a depot at Space Station while the second one is used for servicing from the Orbiter, and in-situ servicing of a payload when carried to the user spacecraft with the OMV.

STS integration is considered an element of the SFHT program. The approach during Phase C/D will be to develop generic documentation (PIPS and annexes) for SFHT usage in the Orbiter bay. The generic documentation package will be an SFHT-specific boilderplate set of plans and annexes that can be tailored for each payload/user desiring superfluid helium resupply.

5.2 MASTER PROGRAM SCHEDULE

The phase C/D master program schedule for the SFHT program is shown in Figure 5.1. Time phasing is based on completion dates for defining requirements, performing design tasks, procuring required components and materials, accomplishing fabrication and assembly, and conducting validation and verification testing.

The initial emphasis has been placed on the systems engineering activities necessary to define requirements and firm up the interfaces. Following concurrence with the requirements and specifications reviewed at the Program Requirements Review (PRR) by NASA-JSC, we will authorize major procurements necessary to support the fabrication and assembly activities, particularly for the Dewar qualification test article. Our plan is to fabricate all components and pieces parts for both the Qual Dewar and the flight article. We will then assembly the Qual Dewar and conduct the qualification tests. While this is occurring, we will be fabricating the other (non Dewar) subsystems, which are to be tested and then flown, in a protoflight approach. Once Dewar qualification is complete, the flight Dewar will be assembled and integrated with the rest of the tanker subsystems. System level tests will then be performed for flight certification and the tanker delivered to NASA-KSC.

For those elements of the SFHT which are to be protoflight, special care must be taken in their validation and the combination of testing and analysis which shows they're good for the 50 mission design life. For both procured and Martin Marietta-manufactured hardware, our verification test program will be initiated at the component level. These component prototype tests are expected to drive out any problems early and are prerequisite to assembly-level prototype testing. This test approach ensures a systematic validation of performance, personnel, and procedures that minimizes risk and establishes high confidence in the system verification activities.

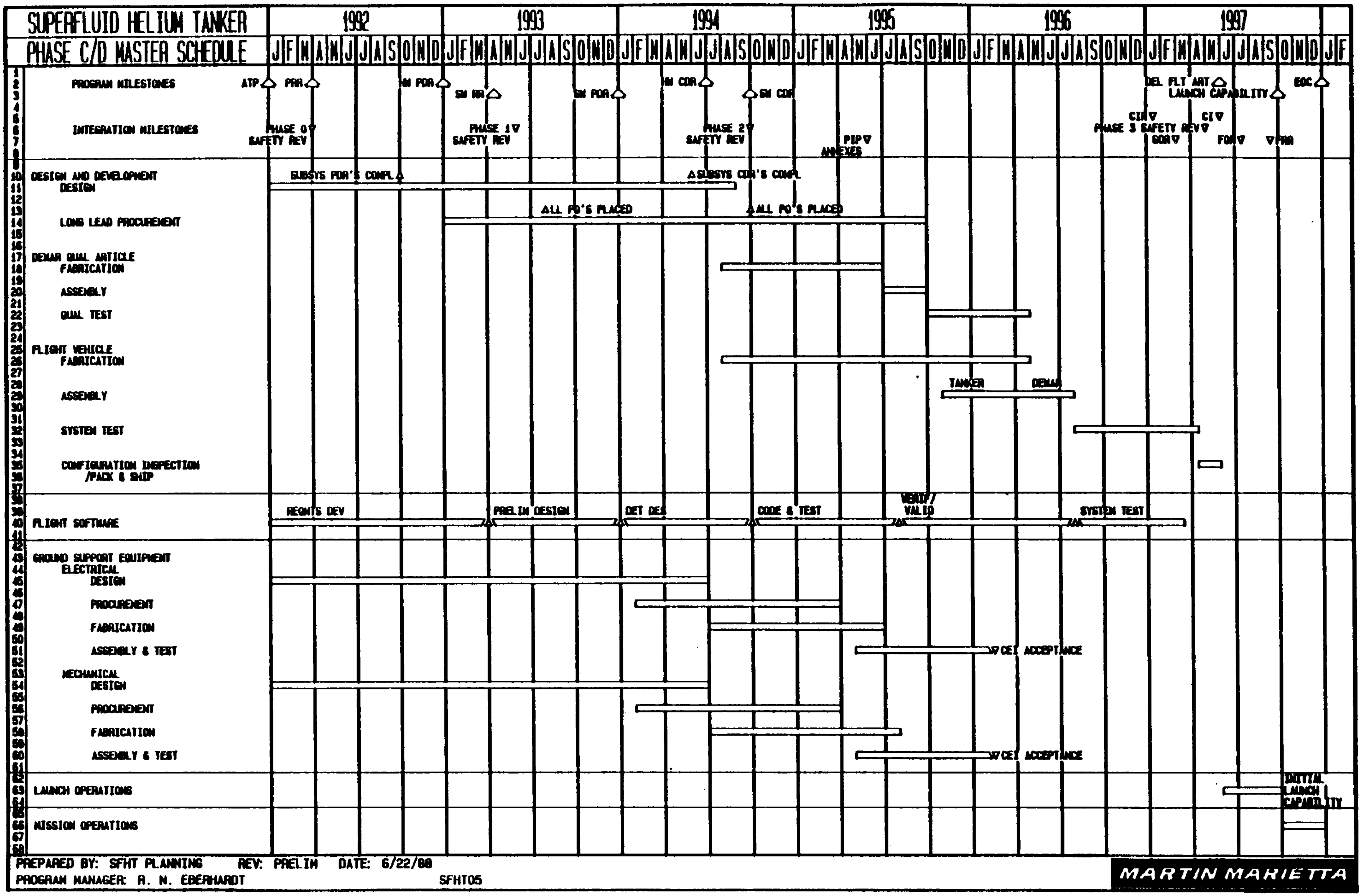


Figure 5.1 Superfluid Helium Tanker Phase C/D Master Schedule

The tanker system test schedule, which is approximately 9 months in duration, is protected by preplanned schedule reserve and will support delivery to NASA-KSC 65 months from ATP. Launch operations also contains preplanned schedule reserve and supports the first flight of the SFHT. As indicated in the schedule, approximately 2 years at the beginning of the program is allocated for design and development.

5.3 WORK BREAKDOWN STRUCTURE

A Work Breakdown Structure (WBS) was developed which provides the framework upon which the programmatic technical, schedule and cost control is established. The WBS is broken down into six levels. The major categories in the WBS at the third level are:

- Program Management
- Systems Engineering
- Design and Development
- Hardware Fabrication, Assembly and Checkout
- Testing
- Software Design, Development and Test
- STS Integration
- Mission Operations

A total of 55 fourth level and fifty level subelements were identified.

5.4 PROGRAM COST ESTIMATE

A Program Cost Estimate has been prepared and will be delivered as a separate volume of our final report. All costs are reported in constant Government Fiscal Year 1988 dollars. The cost estimates reflect that the design of the SFHT incorporates components of like or similar design to those flying in the SHOOT orbital test. One major area of cost difference from the SHOOT system is the Dewar inner storage vessel, outer vacuum jacket, and alumina/epoxy support straps. We've also costed a dedicated Dewar test article for conducting qualification tests. Our structures, thermal, and avionics subsystem costs have been compared to those of the OSCRS design, with appropriate cost deltas generated per differences in the design.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The following summary conclusions were complied during the time period between the Interim Progress Report and this progress report:

- A 6000 liter SFHT still appears to be a reasonable size to handle the reduced user complement specified following the Interim Progress Review. We had selected the 6000 liter capacity during our Task 2 effort using this reduced user complement and found no reason to change that decision.

- We have selected a slightly cylindrical Dewar shape which fits within the fairings of the Delta, Atlas, Titan III and Titan IV launch vehicles. This results in a mixed fleet approach to minizing total mission launch costs. We recommend that the SFHT be designed for compatibility with only one ELV in addition to the Orbiter since interface hardware and ELV unique GSE, operations and integration can result in significant non-recurring and recurring costs to maintain flight compatibility with all ELVs.

- We have selected a ground servicing concept which utilizes a ground heat exchanger for establishing and maintaining the storage Dewar at the desired temperature without activating flight valves to conduct periodic topoffs. This technique allows us to "subcool" the Dewar thermal protection system and meet the eleven day ground hold period following cargo bay door closure. Either pressurized (subcooled) or saturated superfluid conditions in the Dewar are possible.

- Based on a worst case vent analysis for loss of guard vacuum (where we assumed some stratification could develop within the supercritical fluid at the 80 psi burst level), we selected a conventional insulation (non-MLI) to be applied to the inner storage vessel to reduce the heat flux and minimize the size of the vent line.

- Our selected avionics approach ties into the Orbiter GPC for safety-related monitoring and utilizes a redundant computer system on the AFD for transfer monitoring. We baselined the use of the HLVS and TPMS boxes being developed on SHOOT.

- We can meet the design goal mass fraction of 0.25.

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